VOLUME 7
GLOBAL CHANGE IMPACTS

Topic Coordinators
María Begoña García
& Pedro Jordano

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

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What are the major scientific challenges of the first half of the 21st century? Can we establish the priorities for the future? How should the scientific community tackle them?

This book presents the reflections of the Spanish National Research Council (CSIC) on 14 strategic themes established on the basis of their scientific impact and social importance.

Fundamental questions are addressed, including the origin of life, the exploration of the universe, artificial intelligence, the development of clean, safe and efficient energy or the understanding of brain function. The document identifies complex challenges in areas such as health and social sciences and the selected strategic themes cover both basic issues and potential applications of knowledge. Nearly 1,100 researchers from more than 100 CSIC centres and other institutions (public research organisations, universities, etc.) have participated in this analysis. All agree on the need for a multidisciplinary approach and the promotion of collaborative research to enable the implementation of ambitious projects focused on specific topics.

These 14 "White Papers", designed to serve as a frame of reference for the development of the institution's scientific strategy, will provide an insight into the research currently being accomplished at the CSIC, and at the same time, build a global vision of what will be the key scientific challenges over the next decade.

VOLUMES THAT MAKE UP THE WORK

1 *New Foundations for a Sustainable Global Society*
2 *Origins, (Co)Evolution, Diversity and Synthesis of Life*
3 *Genome & Epigenetics*
4 *Challenges in Biomedicine and Health*
5 *Brain, Mind & Behaviour*
6 *Sustainable Primary Production*
7 *Global Change Impacts*
8 *Clean, Safe and Efficient Energy*
9 *Understanding the Basic Components of the Universe, its Structure and Evolution*
10 *Digital and Complex Information*
11 *Artificial Intelligence, Robotics and Data Science*
12 *Our Future? Space, Colonization and Exploration*
13 *Ocean Science Challenges for 2030*
14 *Dynamic Earth: Probing the Past, Preparing for the Future*

CSIC scientific challenges: towards 2030
Challenges coordinated by:
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Volume 7
Global Change Impacts

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VOLUME 7 SUMMARY

ABSTRACT

The environmental sustainability of the Earth system is at risk, and so do human welfare because of our dependency on it. Here, we present challenges to better understand how drivers of global change work, and to minimize their effects on natural and human managed systems, with the aid of new concepts and edge-cutting technology. Their achievement should allow us detect, understand, forecast and mitigate global change impacts related to climate change, the biodiversity crisis, polar regions, and managed ecosystems, and to improve the health of our planet in the coming decades.

KEYWORDS

anthropocene | biodiversity crisis | climate change | environmental monitoring | land use change | polar regions | sustainability of food production systems | healthy planet

GLOBAL CHANGE IMPACTS

Topic Coordinators
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THE CURRENT SCENARIO OF GLOBAL CHANGE

Humans have attained a status not merely of dominance on planet Earth, they are the most drastic force of biological disruption. Global change underpins all those cumulative effects that humans have been inducing since the last millennia, and actually keep inducing at even higher rates, on the Earth system (Dirzo and Raven 2003).

Global science faces the formidable task of providing humanity with the conceptual and technological tools to forecast major threats, manage effective solutions to eliminate or mitigate them, and offer feasible alternatives to alleviate global change effects. Threats have been increasing in the recent time, particularly since the end of the Pleistocene, and are associated in most situations to the direct effects of humans on nature (Barnosky et al. 2012, Novacek 2001). Pollution, greenhouse-effect gas emissions, abuse of water and fossil resources, deforestation, erosion, overhunting and overfishing, loss of wetland areas, the spread of exotic/invasive species, etc. are all different but interconnected faces of what we know as the Anthropocene, i.e., the period when human activity significantly alters the atmosphere composition of our planet, modifies the biogeochemical cycles, shapes the landscape, and is witness to a new (the sixth) mass extinction event. Massive events of biodiversity loss have in common three aspects also shared with the Anthropocene: occur over large tracts of the Earth surface (both terrestrial and marine), span relatively short periods of time, and do affect most groups of biological species.

The recent IPBES (2019) report has described and diagnosed with precision the current situation of the Earth biota and the fast-paced trend to mass extinction that we are facing. Together with the IPCC reports (2018), they provide robust evidence for pervasive changes that humans are inflicting to the Earth system. What this diagnosis has in common with earlier mass extinction and biotic crises on Earth is the rapid and synergic action of multiple stressors on the biota (Brook et al. 2008). Present-day ecosystems are the legacy of a biotic turnover initiated by the onset of glacial-interglacial cycles that began ~2.6 million years ago, and evolved primarily in the absence of *Homo sapiens*. Rapidly changing atmospheric conditions warming above typical interglacial temperatures as CO_2 levels rise, pollution, overfishing and overhunting, invasive species, pathogens, and emerging diseases, and loss of habitats constitute the most extreme ecological stressors that most living species have previously experienced.

A common and successful action for preserving biodiversity, wildlands and oceans is legal protection. About 5,106 km^2 of land and almost none of the oceans were protected in the mid-1970s, and now the figures are close to 17,106 and 10,106 km^2, respectively, and vast marine no- take zones have been established annually since 2000. Large tracts of remote deserts, the Amazon, or the boreal forests are protected, but the current real challenge is to achieve a sustainable production and restoring capacity in or near cities: high demanding sinks of natural resources. As Humankind, a new contract with Nature is needed. If urgent action is taken and environmental policies are deeply revised, a large part of human impacts to nature can be reversed. But observed changes on the Earth system are that fast that even if science and research are put to full work power, they may fail to provide useful forecasts or effective solutions. For instance, the fast-paced changes that are occurring in the Arctic and the long-standing international disputes may block any initiative aiming to a sustainable use of its resources, or even the possibility of generating knowledge to revert these changes. Deep, transformative changes in resource use, international trading, agriculture, use of non-renewable resources, recycling technologies, reduction of emissions and other aspects of human environmental activities are urgently needed. These would require concerted actions at the highest international level, and action policies based on solid scientific knowledge.

The Spanish CSIC and its research groups working on Global Change issues are ready to boost research to forecast and mitigate the effects of ongoing global changes. On the one hand, CSIC research groups collectively have a great potential to carry out synergistic, multidisciplinary projects at large spatial scales. On the other hand, ICTS facilities, historical collections and Interdisciplinary thematic platforms provide an excellent opportunity to deploy medium- and long-term monitoring programs in terrestrial and marine ecosystems, from Mediterranean to polar latitudes, to estimate key environmental indicators and test efficient and natural-based solutions to environmental problems. All this makes CSIC a quite unique and exceptional network of human resources and facilities to carry out scientific projects dealing with the impacts of global change.

WHAT THIS WHITE PAPER CONTAINS

Here we examine some of the most important environmental challenges our society faces in the near future as a consequence of the impact of global change. We do not intend to make an exhaustive compilation of drivers, processes involved, effects and hazards, but to illustrate which of the main ones, and to what extent, can be achieved with CSIC scientists, infrastructures, and collaborations in national and international networks, and to demonstrate the high international visibility of Spanish science in this knowledge area.

Most chapters start by listing knowledge gaps in a conceptual framework, and then we discuss how the development of new technology and long-term monitoring programs involving observational and experimental approaches, together with modeling, might help to forecast future scenarios and better adapt and mitigate environmental problems.

We first start by framing the historical importance of human impact on Earth, in which it has been named “the Anthropocene” (Challenge 1). Knowing what happened in the past and potential causes is the only realistic way of building projections of future scenarios, and thus designing effective mitigation actions. This long-term perspective involves quantitative past reconstruction based on proxies of high resolution stored in paleoenvironmental archives, allowing us to determine, for example, the interaction between climate and human societies, how fast contemporary processes are occurring, potential “tipping points” when abrupt changes occur, and the sensitivity of different environments and geographic regions. The experts list here different challenges addressing the identification and characterization of the main processes involved in rapid climate change and environmental changes, the need to advance on methods and data processing to improve time resolution and space coverage, developing new proxies able to detect rapid changes in the past environments, and advancing in model-data integration at different timescales.

Then, we go through one of the main threats of our planet, tightly linked to the increased atmospheric concentrations of greenhouse gasses: climate change (Challenge 2). The potential impacts of global warming and concomitant socio-economic and environmental costs are well known, and include sea-level rise, polar and mountain glaciers melting, snow cover retreat, more frequent land and marine heatwaves, changes in animal and vegetation phenology and distribution, and more severe forest fires. There are, however, remarkable knowledge gaps and uncertainties, and further work is required to establish a robust and comprehensive assessment of climate change and climate variability, which affects the robustness of future climate projections. Five big challenges have been outlined in this context: 1) to improve the quantification of the rates of change in all physical components (including the rescue and analysis of available historical observations and proxy records to better contextualize and discriminate natural climate variability and the current anthropogenic forcing), 2) to assess the physical processes of climate change, including feedbacks between thermodynamics and dynamics, and interactions between the Earth System components (land-atmosphere-ocean-ice coupling), 3) to quantify the observed changes and identify the triggering factors of extreme events, 4) to reduce uncertainties of climate projections at global and regional scales (which requires sophisticated computational resources and the development of more comprehensive global and regional Earth System models with higher spatial resolution), and 5) to offer reliable and transparent climate services to user communities, since many economic and social activities, as well as policy decisions, depend on the availability of accurate climate information. Also, sustained international initiatives are required to support the continuity of existing analogical observational networks and standardized methodological approaches, which represent the fundamental pillars of climate change assessments.

The next block of key-challenges focusses on how to preserve the threatened biodiversity and its functions (Challenge 3). Biodiversity on Earth is countless, builds on very many interconnected layers of complexity (biological levels, spatio-temporal scales...), and the functional properties of ecological systems are multifactorial and interactive. The authors outline here nine challenges grouped in three major fronts. Firstly, filling knowledge gaps of the relationship between biodiversity and ecosystem services, ecosystem functions of microbial communities, and the evolutionary dynamics of communities. Secondly, advancing in technology like next-generation sequencing, artificial intelligence or remote sensing, which together with citizen science programs constitute a fundamental part of monitoring, both genetically (e.g. sequencing populations of endangered species, discovering microbial diversity) and environmentally (e.g. species presence or distribution shifts, landscape changes…). Emerging technologies have a great potential for massive, large-scale monitoring, but still need to be integrated with observational and experimental evidences, and realistic modelling. Last but not least, seeking solutions for biodiversity conservation, such as those addressed to mitigate the effect of invasive species, halting the loss of pollinators, or managing wild vertebrates. The success of conservation planning and ecosystem-based management depends on our ability both to anticipate species' responses to global change and to manage conflicts arising from ecosystem conservation and economic exploitation, but also on the coordinated implementation of tools such monitoring programs, laws and policies at national and international levels. In the meantime, scientists have to increase their interaction with managers and policymakers, through the implementation of long-term surveillance and monitoring projects addressing urgent questions before arriving to a non-return point of biodiversity loss or decay.

Then, we move to Polar regions (Challenge 4), which are considered the best preserved and natural places on Earth because of the low level of human activity they experience. Besides that, they are exceptional sentinels to monitor global change challenges: both the Arctic and the Antarctic Peninsula are the regions where temperature has raised most and faster than any other Earth's place; the rapid decline in Arctic sea ice extent and volume illustrates the sensitivity of polar regions to global warming; and the strong adaptations of polar wildlife to extremely cold environments makes species highly vulnerable to environmental changes considering their narrow range of tolerance. The remoteness of the polar regions and the complexity of polar research have resulted in many gaps of knowledge in the different spheres of polar systems functioning, interactions, and feedbacks (atmosphere, cryosphere, oceans, biosphere, geosphere). Nine key-challenges are presented here as possible ways for tackling them, aiming at better understanding ozone evolution and its effects on surface climate, polar climate variability and trends, polar changes with satellites (sea ice thickness and extension, glacier melting rate, permafrost…), past ocean dynamics and ice stability under warmer than present conditions, impact of anthropogenic pollutants in the polar regions, biogeochemical cycles of trace metals and their influence on the oceanic productivity in Polar Oceans, the pelagic-benthic coupling in the warming cold, the vulnerability and resilience of Polar aquatic and terrestrial microbial ecosystems to climate change, and finding the best organisms indicators of environmental change. Only by obtaining sound, detailed and long-term knowledge of the polar systems functioning we will be able to stablish efficient and environmentally friendly measures to mitigate the negative effects of current anthropogenic impacts and to protect polar ecosystems.

Unfortunately, human modification of natural systems for the production of food and goods is the norm and one of the major causes of global change (Challenge 5). To cope with the increasing problem generated by a growing and more demanding human population, we urge the development of actions towards more sustainable, climate-proof and resilient production systems. Our understanding of how climate change and land degradation affect current food production and security, and the extent to which they will do in the future is very limited and yet crucial to adopt adaptation and mitigation actions. For that reason, long-term observational and experimental monitoring programs including multiple stressors are necessary to understand complex dynamics, and assess cost and effectiveness of adaptation options. We need, for example, to increase our predictive capability in future environmental scenarios for crops and grazing systems sustainability, nutritional composition of forages, sensitivity of crops and livestock to heat and water stresses, spread and the life-cycle dynamics of pathogens…. A second key challenge deals with fostering resilient and better adapted food production systems: design crop adaptation to changing environments through the development of process-based models that can be used in Decision Support Systems, the use of soil biodiversity to maintain and increase yield production while minimizing ecological footprint, design water efficient production systems through the application of agronomic practices that reduce evapotranspiration losses and lower the water use, develop early warning systems of infectious diseases, aquatic pathogens, marine storms to avoid massive damage to infrastructures etc. The third set of key challenges are focused in mitigating and reducing emissions, by designing carbon efficient landscapes, enhancing soil carbon sequestration, or combining low and high trophic species in complementary cultures of aquatic systems. Finally, the last group of key challenges tackles questions, methods and approaches to foster adaptive management of forests, in order to minimize the direct and indirect effects of climate change, and to better manage wildfires (a major driver of Mediterranean landscape dynamics).

The book ends with the most "problematic and dangerous" part of environmental human legacy, and how the human society deals with environmental risks (Challenge 6). Our unsustainable use of nature, and our steadily increasing energetic demands are bringing the Earth system and its capacity to recover from global changes beyond the environmental boundaries that supported us as a society. Environmental hazards affect socio-economic development and human wellbeing, and constitute a major component of environmental risk management. And despite that the natural capital and the quality of the environment is essential to human wellbeing, there is an increasing number of individuals that live in urban environments, with high levels of pollution and lack of green and natural spaces. Here, the authors make list of challenges that should be addressed for the human species to live with undesirable products resulting from its development: sustainable use of nitrogen to counterbalance atmospheric deposition and the long-lasting effects of artificial fertilizers and pesticides, integrated watersheds management (natural and engineered wetlands) for preserving water resources and their quality, dealing with the environmental impact of the omnipresent plastics by increasing efforts in reducing, reusing and recycling them, and social awareness of the problem they cause, increase of the resilience of marine ecosystems, restoration of the deteriorated marine coastal ecosystems, or the early detection of emergence of zoonotic diseases associated with global change (environmental degradation, land use changes, and climate change). We need nature-based solutions to mitigate urgent environmental problems, and also consider subjective wellbeing issues in the governance of societies for preserving a healthy planet.

EXECUTIVE SUMMARY

The environmental sustainability of the Earth system is at risk, and so do human wellbeing because of our dependency on it. Global environmental changes are not new, but human society is now facing global impacts of anthropogenic causes at an unprecedent fast pace. This book reviews some of the most important environmental challenges created as a consequence of such impacts, and how they can be achieved with the aid of scientific research.

To do so, we first identify knowledge gaps, and then we examine how the development of new technology and long-term monitoring programs involving observational and experimental approaches, together with modeling, might help to seek solutions and forecast future scenarios to better adapt and mitigate environmental problems. This analysis is preceded by the first challenge: framing current global changes into the **long-term reconstruction of natural changes and historical human impact on Earth** ("the Anthropocene"), as a way of improving projections. Then, we examine challenges related to one of the main threats for our planet, of dramatic socio-economic and environmental costs: **climate change** (contextualizing anthropogenic forcing and natural climate variability, interaction of physical processes, forecasting extreme events and climate change at regional scale, provision of climate services to different users). Next two challenges focus on **how to preserve biodiversity and its functions** (unveiling the structure and complexity between biodiversity and ecosystem services, the role of microbial communities, advancing in technology like next-generation sequencing, artificial intelligence or remote sensing, halting the loss of pollinators, reduce invasive species, and managing wild vertebrates), and **monitor biotic and abiotic processes in polar ecosystems**, one of the most remote but sensitive areas to global change (ozone evolution, polar climate variability and trends, current polar changes with satellites, past ocean dynamics and ice stability, impact of anthropogenic pollutants, biogeochemical cycles of trace metals, the vulnerability and resilience of microbial ecosystems, and finding out the most suitable indicators of environmental change). The last two blocks of challenges deal with the **need of developing more sustainable, climate-proof and resilient production systems** (forecasting the sensibility of crops, grazing systems, and the dynamics of pathogens under climate change scenarios, incorporating tools like soil biodiversity, designing water efficient production systems, enhancing soil carbon sequestration, fostering adaptive management of forests, managing wildfires...) and the **need to consider hazards for human wellbeing and look for natural-based solutions** (sustainable use of nitrogen, watersheds management to preserve water resources and their quality, reducing the omnipresence of plastics, increase the resilience of marine ecosystems, restoring deteriorated marine coastal ecosystems, early detection of emergence of zoonotic diseases).

Environmental challenges outlined above must be incorporated in the governance of societies, and the CSIC scientific community can provide knowledge, tools and solutions to design effective policies. The impact of global change is unavoidable, but our success in preserving the important services provided by nature, building sustainable and resilient productive systems, and incorporating risk management, will determine the future human wellbeing in a healthy planet.

PARTICIPATING RESEARCHERS AND CENTERS

82 researchers working at 31 CSIC Institutes, together with scientists working at five national and international Universities, one national research center and one company have participated in this volume (coordinators of the chapters and the with paper in bold).

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CHALLENGE 1

ABSTRACT

Facing current climate and environmental crises needs long-term series of Earth Dynamics and anthropogenic pressures on the Planet. Numerous geological, chemical and biological natural archives capture large-scale, multi-temporal, abrupt, and often irreversible shifts in environmental and climate systems, providing an opportunity to better understand and therefore predict potential future impacts of the present anthropogenic warming and Humankind impact on the Planet. By providing robust, reliable, quantitative, detailed, high-resolution and long paleoclimate and paleoenvironmental data series, paleoclimatology and paleoenvironmental research place present climate variability and ecological crises in a long-term perspective to understand climate forcing mechanisms and environmental processes and responses. The success of science-based solutions to the global risks in the 21st century will strongly rely on our capacity to transfer this knowledge to politicians, managers, and society.

KEYWORDS

anthropocene | paleodata | paleoclimate modelling | paleoarchives | past global changes

CHALLENGE 1

PAST GLOBAL CHANGES: A CONTEXT TO THE ANTHROPOCENE

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1. INTRODUCTION AND GENERAL DESCRIPTION

The Anthropocene is defined as the current period in Earth History in which the humankind appears as one of the main drivers in shaping the landscape, modifying main biogeochemical cycles, stressing the biodiversity and altering the atmosphere composition of our planet. In spite that formal definition and boundaries for this new geological Earth period are controversial and not yet agreed by the scientific community (Rull, 2018; Zalasiewicz et al., 2019), there are multiple evidences that indicate the unique nature of the last 50 years (otherwise defined as the Great Acceleration), as the rate of change of surface biogeochemical processes has increased, hand in hand with the increase in population and the growing demand of resources. The scientific community has been alerting about the dramatic trend in many drivers of global change (*stressors*) with consequences that can go beyond nowadays projections if some tipping points are reached (Rockström et al., 2009). Society demands progressively improved projections of future climate change that allow for designing more effective mitigation actions. In order to achieve them, a better knowledge of processes contributing to climate variability and change is needed. Undoubtedly, that knowledge roots on long-term observations of

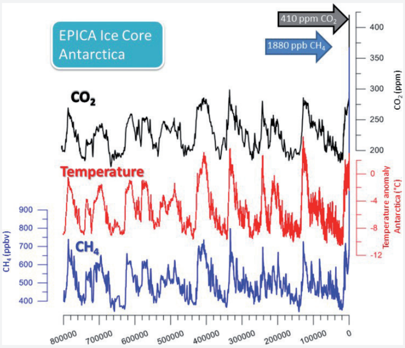


FIGURE 1—Variations of temperature (red), atmospheric carbon dioxide (black) and methane (blue) over the past 800,000 years, from the EPICA Dome C ice core in Antarctica. Modern values (year 2019) of carbon dioxide and methane are indicated by arrows. Modified from http:// www.iceandclimate.nbi. ku.dk

natural variability (Abram et al., 2016), performed on current ecological monitoring surveys (eg. LTER initiative) and climate, as well as on reconstructions provided by natural and documentary archives that allow to look further back in time than available observational data series which only record 150 years in the best cases. The use of state of the art Earth System Models (ESM) can provide mechanistic understanding of such processes in model-data comparison exercises.

Long-term and quantitative reconstructions of past Earth Dynamics at multiannual (or higher) time resolution should serve to look for analogues of present-day climate and environment, characterizing tipping points, understanding past climate and ecological feedbacks, and accurately describing and quantifying the anthropogenic effects on climate. Thus, by diving into paleoenvironmental/paleoclimate archives, we can determine if we are facing unprecedented changes compared to the natural baseline conditions defined by previous periods. Considering climate changes recorded by Antarctic ice cores, it is evident the unprecedented values in greenhouse gasses attained nowadays in the context of last 800,000 years (Figure 1). Importantly, many drivers of past global changes are similar to those stressors playing a key role today, but the rates of change and consequences are magnified. In fact, the velocity at which current global change is occurring is likely the main difference with previous periods of change. In addition, reconstructions of past interactions allow understanding the feedbacks that pushed the system into a different mode of operation. The "tipping points", when such abrupt changes occur, are notoriously hard to predict and paleoreconstructions aid to reduce the uncertainty in the current projections.

Numerical Earth System Models (ESM) experiments are designed, as in the case of laboratory experiments, to reveal potential cause-effect relationships. The main questions addressed by the most recent phases of the Coupled- and Paleo-Model Intercomparison Projects (CMIPs, PMIPs; Eyring et al., 2016; Taylor et al., 2012) target understanding how the Earth System responds to forcing, what are the origins and consequences of systematic model biases, and how can we assess future climate changes given internal climate variability, predictability and uncertainties in scenarios. In order to address these questions, current and future simulation efforts that span timescales much wider than the post-1850 historical period are needed. Past climate states can be very different from present climate, thus paleo model-data comparison provide stringent tests for state-of-the-art models and a way to assess whether their sensitivity to forcings is compatible with past climate observations.

The study of past global changes also helps to characterize the responsiveness of biomes and geographic regions to climate and environmental changes in the past and, thus, to identify which ones are more sensitive and endangered today (otherwise called hotspots). The polar regions, and specially the Arctic, are showing the most rapid rate of warming worldwide, with unprecedented sea-ice loss and ecological shifts with unknown consequences (e.g. ice-associated marine mammals and commercial fish stocks, and abrupt and dramatic collapse of the West Antarctic ice sheet). The Mediterranean area represents another key region both in terms of high biodiversity and long-term human occupation history. Its intrinsic features (summer droughts, periodical water shortages and relatively high human density population) make its terrestrial and marine ecosystems highly vulnerable to the current anthropogenic global warming and increasing human pressures. Furthermore, this key region is an ideal natural laboratory to characterize past society's resilience and adaptation to past climate/environmental fluctuations and tipping points. Previous examples of different scenarios and responses to climate and environmental abrupt changes including resilience, adaptation, and sometimes collapse of societies can be found in southern Iberia Peninsula: the Argaric culture collapse at around 4 millennia ago driven by both aridity crisis and strong anthropogenic impact including deforestations and fires (Carrión et al., 2007) is a good example. Besides, the migrations of hunter-gathered groups during the Early Holocene in the Ebro and neighbouring mountains reflect the contrasted and complex responses obtained from nearby areas (González-Sampériz et al., 2009). Positive feedbacks with great economic expansions and cultural success partially related with favourable climate conditions also occurred, e.g. the Egyptian culture associated to regular Nile floods or the Viking settlement in Greenland and Terranova regions when the Artic was navigable during the Medieval Climate Anomaly (10th -12th centuries).

In summary, robust and quantitative paleodata, as well as mechanistic understanding coming from modelling exercises, are urgently needed to provide the climatic and ecological framework to understand recent changes, slow down the impacts and improve adaptations to one of the most compelling challenges that humankind is presently facing.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

There is a scientific consensus that the current warming trend, particularly since the mid-20th century, is the result of human activities and the rates of change are unprecedented at least during the Holocene. As also stated in Thematics 13 and 14, one of the key scientific challenges for the 21st century is to understand the impacts of the present temperature rise in all Earth spheres and the underlying mechanisms and feedbacks responsible of the current situation, including anthropogenic pressures. The goals of this Chapter have been oriented following this basic science perspective. Many other research and consultant organizations such as the United Nations, with their Sustainable Development Goals (https://www.un.org/sustainabledevelopment/sustainable-development-goals) and the European Environment Agency (https://www.eea.europa.eu/), the Intergovernmental Panel on Climate Change (https://www.ipcc.ch), the United States Environmental Protection Agency (https://www.epa.gov), and Australia's national science research agency (https://www.climatechangeinaustralia.gov.au/en) are also aligned with the basic science perspective. These organizations are promoting the creation of indicators of climate and environmental change that are being used to understand the rapid changes that our planet is suffering and design friendly and sound mitigation strategies in the line of the Green Deal of the European Commission and the research program Horizon-Europe.

3. KEY CHALLENGING POINTS

To provide the necessary context to the Anthropocene first we need to improve our understanding of the **PROCESSES** controlling past global changes, focusing on those close to a tipping point or those that denote a gap of knowledge. One of the main challenges for the scientific community is to identify the dynamics involved in rapid and irreversible past environmental and climate changes and their impacts. To do that, we need to improve the **RECONSTRUCTION** of past global changes, with new and improved methods and proxies, with higher temporal and spatial resolution, with better quantification and calibration strategies and with a generalized use of statistical tools and databases resources. The third challenge is devoted to paleoclimate and paleoenvironmental **MODELLING**. Models need to span the simulations time intervals to the past, with improved and accurate representation of proxy-based forcing reconstructions and increasing computational resources. Modelling efforts should dedicate to incorporate all identified significant forcings (solar, volcanism, aerosol, anthropogenic), to ensure a meaningful advance in the understanding of processes and feedbacks while dedicating more efforts to model-data comparison.

3.1. Main processes involved in rapid climate and environmental changes

The goal is to identify and characterize the processes that cause past climate variability, discriminate their triggering mechanisms (drivers), understand feedbacks and thresholds and evaluate their impacts on different Earth systems in the past, considering the ecosystems resilience and the time needed to recover after an event. This research has to be directed to better understand processes of rapid climate and environmental change that are active and amplified (and or interacting with) anthropogenic impact on the planet.

Oceans

The Ocean's meridional overturning circulation

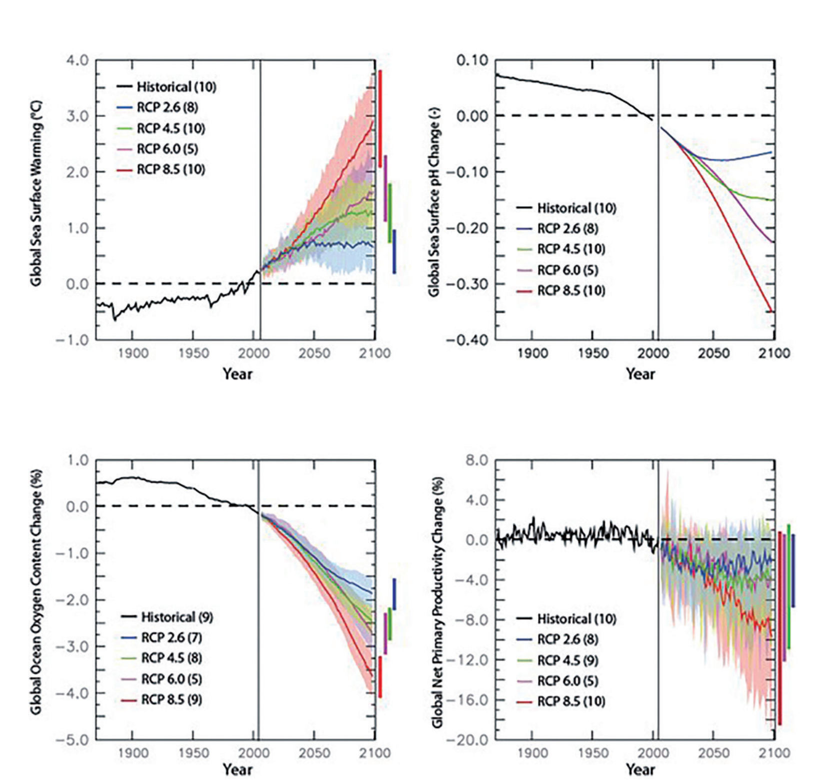
During the boreal winter months, sea winds and warm waters are directed towards the European margin from the subtropical regions to the pole. Cooling and sinking of surface waters at high North Atlantic latitudes play a vital role in the ventilation of the deep ocean and the modulation of regional climate, through the release of evaporative heat. The decrease or absence of deep water production in the North Atlantic (AMOC) caused strong cooling over Europe in the past: cold episodes taking place there when the predominance of deep-water formation changed from northern to southern sourced deep-waters, as traced by glacier ice and marine sediment cores (Martrat et al., 2007). Climate change scenarios point to a weakening of the transports (Heuzé et al., 2015); in fact, the Mediterranean has already experienced several intervals of circulation perturbations over the past five centuries (Incarbona et al., 2016). While in the absence of a strong AMOC reduction, for instance, the Arctic and Mediterranean regions are to warm two to three times the global annual average, an AMOC collapse could lead to a reduction in surface air temperatures of up to 10°C in the North Atlantic (Weijer et al., 2019). Key challenge goals to cover the gaps in our knowledge can be addressed by (i) studying the metrics that robustly show Atlantic and Southern Meridional (AMOC/SMOC) and Mediterranean circulations collapses with both data archives and among a wide range of models; (ii) distribution of a feasible long-term operational monitoring system and (iii) extrapolation by decadal prediction systems.

Ocean stressors

Oceans are being stressed as a result of human activities (marine pollution, overfishing, habitat destruction, eutrophication) with four major stressors (ocean warming, ocean acidification, ocean deoxygenation and changes in primary productivity) that impact on a global scale, threatening marine organisms, populations and ecosystems, and compromising the services that oceans provide to humanity (Figure 2). Their cumulative impact is expected to be amplified over the coming decades (Frölicher et al., 2016; Halpern et al., 2019), while different combinations may lead to synergistic impacts greater than the sum of their individual effects. There is an urgent need to explore and understand this new reality and to establish how to meet human needs in a sustainable and equitable way.

- **Ocean warming**: This is the global pressure that has concentrated most of the scientific attention since it is critically impacting a long list of ecosystems, being the tropical coral reefs the most iconic example, strongly damaged by the progressively intensified bleaching events. Ocean warming is heterogeneous and there is a need to further understand trends in the recent past, at high resolution, making use of sediment cores from high sedimentation rates regions and other archives such as corals.
- **Acidification:** Since the mid-2000s, research on this stressor has expanded exponentially, providing evidences on its detrimental effects over a wide range of marine organisms. The development of proxies for the reconstruction of past levels in pH, particularly boron isotopes and B/Ca ratios in calcifying organisms, allowed scientists to gain insight on short- and long-term variability of pH. The goal now is to exploit these proxies (i) in high resolution archives of the most recent past (deep sea

FIGURE 2–Ocean stressors (Bopp et al., 2013). Model-mean time series of global sea surface warming (ºC), surface pH change (pH unit), ocean O_2 content change (%),and global NPP change (%) over 1870–2100 using historical simulations as well as all RCP simulations. Shading indicates one inter-model standard deviation. All variables are plotted relative to 1990–1999.



sediments, tropical and cold water corals) to determine the modern acidification trend in the Anthropocene, and (ii) in older periods of time (i.e. glacial/interglacial timescales) to better constrain the changes in earth system processes accompanying the well-known variations in atmospheric CO_2.

- **Deoxygenation**: Ocean oxygen levels have been decreasing since 1950 Common Era (CE), impacting marine life and biogeochemical processes (Breitburg et al., 2018). Ocean deoxygenation is expanding the already vulnerable oxygen minimum zones and causing severe and adverse changes in marine ecosystems, both at global and local scale. In coastal areas and semi-enclosed seas, the delivery of nutrients from sewage, agriculture water discharges and airborne sources stimulate algal blooms which consume oxygen driving hypoxia. At the same time, climate warming intensifies the effects from eutrophication and reduces the air to sea oxygen flux and ventilation of the ocean interior. In order to further constrain the potential impact of the current deoxygenation, it is crucial to determine past changes in dissolved oxygen, for which quantitative proxies are still under development.

- **Primary productivity**: The combined and synergistic effects of the aforementioned major ocean stressors have an impact on primary production, which is crucial to sustaining the future ocean and the global carbon cycle. Projections of future trends in marine productivity present high uncertainties but the general view is that it will decrease globally on average (Bopp et al., 2013). It is essential now to contextualize past changes in marine production, from the analyses of high resolution sediment cores in productive areas (e.g. upwelling regions), but also including the characterisation of past changes in nutrient chemistry (i.e. phosphate, nitrogen, silicon, iron) and vertical mixing.

The polar cryosphere

Antarctic and Arctic ice sheets are the main planetary freshwater reservoirs (99%). Their ice sheet dynamics has a global impact on sea level rise, ocean structure and circulation, marine productivity, and atmospheric CO_2 sequestration and circulation patterns, among others. Detailed reconstructions based on ocean and lake sediment records have yielded evidence for the strong impact that abrupt and rapid climate changes have on sea level, ecosystems and surface processes. For example, ice sheet calving, has been shown to be extremely sensitive to temperature changes and can occur remarkably fast and affect extensive areas. This melting, together with the thermal expansion of the seawater due to temperature rise, will largely affect coastal infrastructures around the globe with disastrous economic consequences. Since 1880 CE, the sea level measurements show that it has already risen 21 - 24 cm. To decipher the mechanisms associated with abrupt melting and rapid climate changes in polar regions, this challenge targets are: 1) understanding the timing and the patterns of environmental variability associated with past abrupt climate changes in polar regions; 2) exploring global connections in the climate system and 3) identifying ice sheet calving threshold. To address these will require:

1) identification and validation of new proxies for meltwater input and icebergs calving reconstruction, 2) recovering of high resolution proximal records in polar margins, which remain really scarce, especially in the southern high-latitudes, and 3) characterization of past and present climate conditions and feedbacks that have ruled these calving periods.

Atmospheric aerosols

Limiting global warming to 2.0°C as stated in the Paris agreement at COP21 in 2015 requires strong mitigation of anthropogenic greenhouse gas (GHG) emissions. Alongside, emissions of anthropogenic aerosols will decline as a result of their co-emission with GHG and the improvement of air quality. To date, the combined climate effect of GHG and aerosol emissions is poorly constrained (Samset et al., 2018), but it is evidenced that removing aerosols will heat global mean surface by 0.5–1.1°C, and cause more extreme weather events. Recent mitigation policies have been effective in the removal of "cooling" aerosols such as sulphates and nitrates but inadequate in the elimination of warming ones such as black carbon (BC). The continuation over time of this scenario may amplify current warming, with other related-effects on ecosystem fertilization by nitrogen deposition, which promotes CO_2 removal from the atmosphere, thereby buffering human effects on global radiative forcing (Tipping et al., 2017). Improved characterization of natural emissions and their radiative effects can therefore increase the accuracy of global climate model projections.

It is well-known that feedbacks between the global dust cycle and the climate system might have amplified past climate changes. Bearing in mind that the projected climate changes may boost mineral dust emissions to the atmosphere, the sensitivity to past climate changes raises the question of how the global dust cycle will respond and of whether the resulting dust–climate feedback will oppose or enhance those climate changes. Unfortunately, uncertainties in net climate forcing from aerosols are substantially limiting our understanding of the magnitude of the historical radiative forcing due to anthropogenic aerosol emissions (Hamilton et al., 2018). Improvements in historical reconstructions of natural and early anthropogenic emissions are thus a demand. Key aspects to reduce uncertainties in future predictions are (i) the exploitation of new/improved Earth system models, (ii) a better understanding and evaluation of the controlling processes, and (iii) the study of past aerosol records stored in ice or sediments.

Extreme temperature and hydroclimatic events

Extreme climate events such as heat waves, avalanches, cold, snow, ice, large hail, frost, severe winds, storms, heavy rain, fluvial or coastal flooding, droughts and wildfires are a reason for concern given their important physical, economic, social and political implications (Masson-Delmotte, 2019). Understanding the links between extreme occurrence and climate variability is critical to anticipate impacts and vulnerability for planning adaptation. Paleoclimate analysis has demonstrated how shifts in climate produce changes in the magnitude and frequency of extremes. The study of long-term records of past climate extremes provides a realistic understanding of how the present climate differs from past periods, to simulate extreme events under global warming scenarios. The main goals on the characterization of extreme events in the past are:

- Produce regional multiproxy reconstructions for detection of periods with higher concentration of extreme events by using sedimentary and biological archives (fluvial and lake sediments, glacier ice, speleothems, trees, etc) and documentary evidence (extreme temperatures (Barriopedro et al., 2011); floods (Blöschl et al., 2020); droughts (Cook et al., 2015)).
- Inclusion of palaeorecords tracing aerosol, pollution dispersal and soil loss to help in deciphering their role on extreme events, which is linked to processes as yet to be explored. Current datasets are limited to experimental monitoring stations that barely span the last two decades.
- Identification of atmospheric and oceanic climate modes of variability leading to extremes and characterization of their variability in the past (changes in ENSO / monsoonal systems, extreme negative phases of NAO, etc).
- Work on data assimilation with particular emphasis on regional reconstructions of extreme events during past analogues of warming and transient climate periods.
- Development of statistical tools to detect non-stationarity break points in proxy series, and for including climate covariates in frequency analysis.

It is especially relevant the investigation of compound events, i.e. multiple hazards that combine to produce increased risks and impacts. For example, the occurrence of drought combined with extreme heat will increase the risk of wildfires and consequent losses. A changing climate may alter the interaction between hazards which in turn could exceed the adaptive capacity or resilience of the human and natural systems more quickly than individual events.

Biogeochemical cycles

Increasing concern about human manipulation of global biogeochemical cycles requires a long-term approach using data available in paleorecords to assess (1) the nutrient status of aquatic and terrestrial systems, (2) their baseline conditions, and (3) the long-term processes controlling elemental fluxes on decadal to millennial timescales.

- **Carbon cycle**: Studies of land–ocean–atmosphere integration should be strengthened to include and quantify the processes that connect land carbon, inland waters, coastal oceans and open oceans on different time scales. The Holocene, when significant changes in the carbon cycle and temperature were recorded, is an interesting period to explore the mechanisms responsible for pCO_2 increase (e.g. land carbon storage, the role of the ocean acting as a source or sink) and their links to climate (Brovkin et al., 2019).
- **N, P and O cycles**. Currently there is a progressive eutrophication of lacustrine systems and coastal areas as a result of the anthropogenic oversupply of nutrients causing a productivity increase and a consequent oxygen consumption leading to hypoxia and denitrification. The use of paleorecords can help to discern what factors influence nutrient cycling in natural settings over decadal to millennial time periods and establish their environmental consequences and feedbacks. That investigation should be prioritized to evaluate the possible consequences of future perturbations and the available alternatives to mitigate them (McLauchlan et al., 2013).
- **Metals (Pb, Hg)**. Enhanced input of metal pollutants in the atmosphere is affecting ecosystem function and biodiversity in profound ways. In this respect, mercury is an emission by-product of the extensive burning of coal and crude oil and its increasing accumulation constitutes an environmental deleterious impact. Those metals were delivered in large amounts in the past millennia (mining and smelting activities), allowing to explore the environmental consequences by using sedimentary records preserved in remote systems not overprinted by local anthropogenic processes (Catalan et al., 2013). The main goals are: (1) determining changes in anthropogenic trace metal concentrations

contextualizing current values with pre-industrial levels, (2) discerning site-specific processes that influence their enrichments, (3) evaluating the impact of past pollutants on the biological communities (function, diversity) and on the natural geochemical processes (coastal area, lake, peatbog).

- **Organic contaminants**. Organic contaminants and wastes (eg. polycyclic aromatic hydrocarbons –PAH) are compounds primarily composed of carbon, hydrogen, and potentially other elements and are currently present in the soil, water, air, and sometimes food, resulting in harmful effects for human and environmental health (Pal et al., 2010). Paleoenvironmental records hold the potential to trace the presence of these compounds in the recent past and help to (1) establish the timing of contamination of previous pristine environments, (2) quantify the impact threshold above which there are harmful effects on the environment, and (3) understand the complexity of transport processes (e.g. volatile compounds) to finally contribute to future regulations.

Interactions of past climate and human activities with vegetation

Ecological and vegetation disturbance (overgrazing, agricultural pressure, deforestation, fire, expansion of invasive species, pests, diseases, deterioration caused by catastrophic storms, etc), mediated by both climate variability and human impact, is a major driver of ecosystem function, structure and composition. Vegetation changes take place over a long period and become evident gradually or abruptly, depending on the disturbance, and usually (not always) involve a reduction in biomass and changes in the structure and species composition (biodiversity). Some crises may also lead to an increase in biodiversity after the perturbation and during the adaptation to a new system. Ecosystems have been shaped by millennia of intense land use that makes difficult to distinguish the impacts of human disturbance and climatic change on past vegetation dynamics (Figure 3). Paleoecological reconstructions assess the natural dynamics of ecosystems and investigate how these systems respond to different drivers in different context. We outline here two of the main drivers affecting past vegetation changes:

- **Humankind**. Anthropogenic activities have been suggested as one of the major drivers of vegetation change in the Iberian Peninsula at least for the last 7500 years. In this sense, the improved linkage of archaeological and paleoecological records is essential to understand the timing and extent of alterations on natural vegetation during the past millennia.

FIGURE 3—Human-environment interactions in the past. Images corresponding to (A) fires, (B) agriculture (image of cattle herder from Egypt found in the Sennedjem tomb in Deir-el-Medina), (C) landscape of Roman mining (Las Médulas, León) and (D) rock painting of deer hunting in La Valltorta cave (Castellón).

- **Fire**. Fire acts both as a powerful filter of the species pool and as a strong driver of evolutionary selection. Most paleofire studies have reconstructed fire history and in certain cases fire regime. However, considering the regional variability on a spatial scale is necessary. The origin of fire is not always clear since it is both a natural element involved in Mediterranean regions and a process employed by ancient societies for agriculture and grazing maintenance systems.

Additionally, paleobotanical records provide abundant evidence for plant spread and migration together with indications for extinctions, exterminations and range shifts. The study of past forest change provides a necessary historical context for evaluating conservation policies. Analyses based on fossil and genetic data are necessary to advance our understanding of tree colonization, adaptation, and extinction, revealing cryptic refugia which potentially safeguard the persistence of biodiversity over centuries or millennia. The identification of those places should be a priority in restoration and conservation planning.

Human societies and climate change interactions in the past.
Climate change has been an important contributor to the development of human society throughout time. Because of current social development, it is very unlikely for climate change today to produce comparable impacts as those that occurred in the past. Nonetheless, tackling such historical cases can improve our understanding of the nature of human-climate-ecosystem interactions, as well as the vulnerability and sustainability of small-scale societies in the context of climate change, determining in some cases societal success or collapse.

However, causes and tempos of different social dynamics of change must be considered with caution. Models used to understand the collapse of state-level societies in tropical or arid environments, such as the Classic Maya or Akkadian states respectively, cannot be applied to terminal episodes in far less integrated societies in more temperate environments. Not only are regular cycles of socio-political changes and fragmentation intrinsic features in societies, but different ecosystems present varying degrees of vulnerability and different opportunities for adaptation and resilience of human populations. In fact, a complex landscape 'co-evolution' results for the interactions between climate, ecosystems and human activities through time, and there is clearly a need of collaboration between the historical-archaeological and the paleoenvironmental sciences to better understand these complex interactions (Figure 3) which, undoubtedly, also affect our current and future scenarios of global change.

3.2. Advances in proxies for past global changes

To understand and quantify processes in the past we need to advance on the methods and data processing, improving time resolution and space coverage of available records and developing new proxies able to detect rapid changes in the past environments. It is also crucial to dedicate more efforts to the creation and extended use of databases. Critical issues involving accuracy of the chronology, statistical treatment of the results and sensitivity and frequency in the proxy response to forcing mechanisms remain challenges for future investigations.

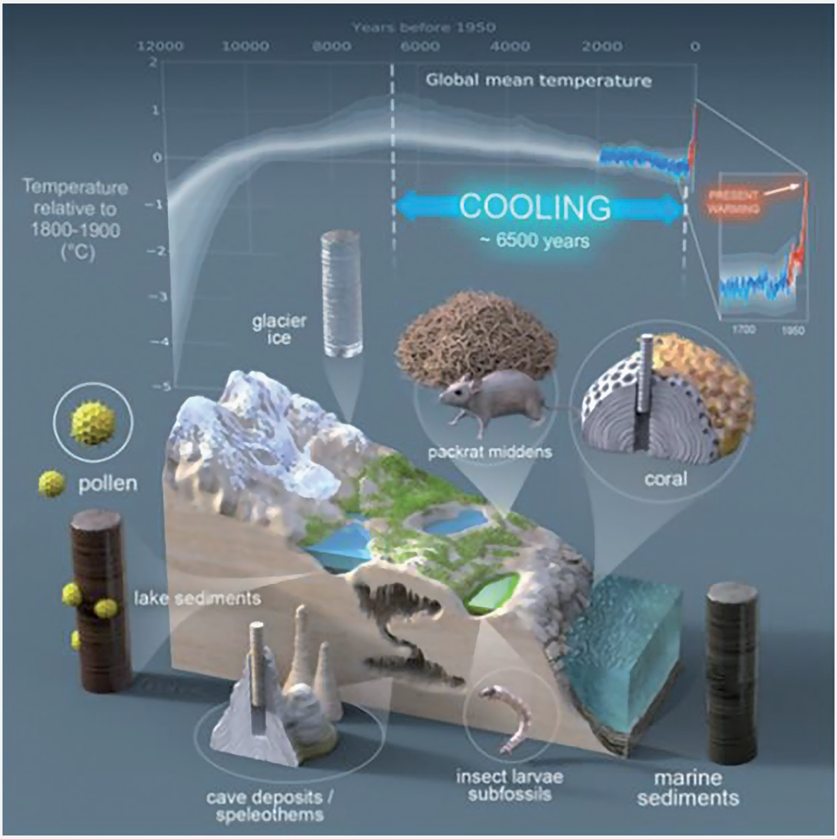
Build and maintain open, up to date, interactive and modern metadatabases
Database compilations help in understanding key climate variables and processes and are available for different paleoclimate archives (bivalve, borehole,

coral, documents, glacier ice, lake sediment, marine sediment, sclerosponge, speleothem, trees and many more) for global surface temperatures (PAGES2k Consortium et al., 2017), hydroclimate (Konecky et al., 2020) or modes of climate variability (Hernández et al., 2020). The increasingly amount of datasets needs synthesis efforts with clear pre-defined criteria to ensure quality control: (i) records have to be archived in a permanent publicly accessible data repository (examples in NOAA-WDS Paleoclimatology or PANGAEA); (ii) known relation between proxy value and climate or environmental parameter; (iii) minimum record duration over the time span of reference; (iv) quantifiable resolution, from seasonal to centennial; (v) chronological accuracy, i.e. number, position and uncertainties of control points. Open-data principles require to make all data used in modern paleoclimate databases **F**indable, **A**ccessible, **I**nteroperable and **R**eusable (**FAIR**; Wilkinson et al., 2016), whether referring to (1) data described in previous publications, including data-reanalysis products, and third-party unpublished data ("input data"), and/or (2) data generated as an outcome of the study ("output data"). In the Big Data age, analyzing large "paleo" data volumes critically hinges on clear standardized in format and terminology (Khider et al., 2019). This is one key challenge for natural (land, ocean) and documentary archives. Synthesis work and standards will allow researchers to curate and access datasets in online hubs while creating a common vocabulary for them, maximizing their reuse value, particularly for comparison to climate model simulations, a vital process to detect regional climate complexities.

Improving proxy resolution and spatial coverage

Efforts to increase temporal and spatial resolution in paleorecords are necessary to encompass a better and robust understanding of processes, mechanisms, impacts and ecosystem to develop new scientific knowledge regarding current global climate. An important outcome of increasing time resolution in paleorecords is the ability to identify and characterize past extreme events (e.g. droughts, floods, heat waves, hurricanes, wildfires). Since extreme events have long periodicities, the instrumental period is too short to provide an adequate characterization and a robust risk assessment of their probability. High resolution paleoclimatology involves studies for past climate variations at a temporal scale that is comparable to that of instrumental data, which in practice, means annually resolved records. Some paleoarchives (Figure 4) store seasonal information *per se* (e. g. tree rings width as an indicator of summer temperatures) but usually a meticulous sampling is required to gain the full proxy potential and reach, in the best cases, annual signals.

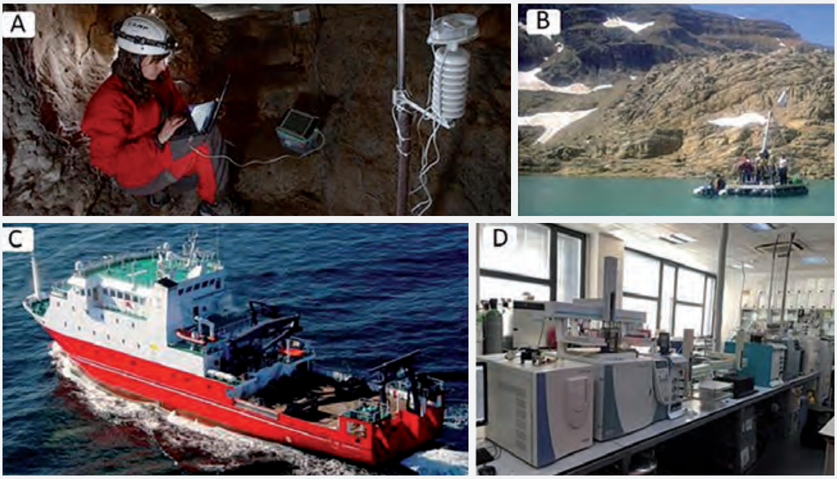
FIGURE 4–Past climate changes over the Holocene show that the Earth was warmest around 6500 years ago when global average temperature was likely about 0.7°C higher than during the 1800s. Global warming since then has reached about 1°C (Kaufman et al., 2020). This image also shows several archives of paleoclimate and paleoenvironmental information. Illustration by Victor O. Leshyk.



New analytical techniques (e.g. SIMS, LA-ICP-MS) offer many unexplored avenues of research in high resolution (e.g. continuous measurements, smaller sample amount requirements). The technological goal is to develop new methods to facilitate the continuous measurement of different variables obtaining robust and quantitative results.

The increasing recognition over the last few years of the necessity to understand the spatio-temporal evolution of climate trends, ecological impacts and extreme events has brought to light the still patchy coverage in available

FIGURE 5—Images of field and laboratory studies that we conduct in Paleoclimate and Paleoenvironmental sciences. (A) Cave monitoring in Las Güixas cave (Villanúa, Huesca); (B) coring Marbore Lake in the Pyrenees using a platform; (C) the oceanographic vessel Sarmiento de Gamboa (http://www.utm.csic.es) and (D) the stable isotope laboratory from the Instituto Andaluz de Ciencias de la Tierra (IACT-CSIC).



paleoreconstructions. Some remote regions remain less represented, such as large areas of the Pacific Ocean, Africa, the Amazon and Australia. Some of this poor representation is due to absence of sites (e.g. regions that have unsuitable climates to support ice sheets, trees, lakes or bogs), but at smaller scales there could be sampling biases related to the complex and expensive logistical infrastructure needed to properly sample these remote areas. One challenge to obtain complete representation of paleoclimate variations worldwide is to increase the spatial coverage focusing new studies in poorly represented regions.

Development of new proxies and quality control of proxy reconstructions

Reliable reconstructions of past climates require a well-suited battery of proxies capable of providing quantitative environmental information related to the physical, chemical and biological conditions of the past environment (Figure 5).

For a climate/environment proxy to be useful, we need to (i) improve the analytical measuring capabilities and (ii) understand the driving processes behind the analyzed proxy. The development in recent years of advanced and sophisticated analytical instruments with increased sensitivity and accuracy has opened up the possibility of measuring new and promising chemical tracers. On the other hand, the use of a multi-proxy approach (several tracers informing on the same variable) has proved to be very valuable to resolve discrepancies and/or inconsistencies among proxies, given that a single proxy is often affected by several processes or environmental conditions. The following goals have been identified:

- Explore the potential of new measurements now possible through the **development of techniques** capable of high accurate geochemical analyses, such as Multicollector-ICP-MS, and improve the precision capabilities of existing analytical methodologies that are now hampered by the relatively large amount of sample needed (e.g. boron and neodymium isotopes on marine sediments or carbonate clumped isotope thermometry on speleothems). Also, in the marine realm, several trace metal isotopes (e.g.: Fe, Zn, Cd, Mo, Ba...) are being tested as potential marine paleoproductivity and/or redox conditions proxies. The recently developed GC-MS Q Exactive Orbitrap systems provide high sensitivity and selectivity which greatly enhances the identification and quantification of sedimentary organic molecules in marine and freshwater ecosystems.
- Develop, and improve existing, **proxy-to-environment calibrations** in order to obtain meaningful and quantitative reconstructions of past climates. In this regard, some of the proxies where special effort is needed given the relevance of the reconstructed variable include: (i) Specific organic biomarkers preserved in speleothems and marine sediments as proxies for surrounding vegetation types, storms, desertification and bacterial activity, (ii) carbon isotopes and trace elements (I/Ca and U/Ca) in foraminifera, organic biomarkers and trace metal isotopes from marine sediments as proxies for dissolved oxygen and deep water ventilation, and (iii) proxies of marine export production, which include tracers of redox conditions, particle fluxes (barite and molecular biomarkers) and nutrient tracers.
- Adapt and develop new **statistical tools** to ensure the robust and quantitative reconstruction of climate variables from high-resolution and multi-proxy characterization of natural archives, encouraging a close collaboration between statisticians and paleoclimatologists. This challenge should focus on (i) developing new calibration methodologies by employing cutting-edge statistical tools such as machine learning and bayesian approaches, (ii) calculating and incorporating to the paleodata

all uncertainties associated to chronological models, and (iii) developing statistical tools to correctly assess the frequency behavior of unevenly-spaced temporal series.

3.3. Advances in modelling and model-data integration at different timescales

Earth System Models (ESM) represent the highest level in the hierarchy of complexity of coupled general circulation models (GCMs) (McGuffie and Henderson-Sellers, 2014). The last generations ESMs have evolved to represent realistically many of the climate processes to analyze sensitivity to changes and interactions between climate subsystems, ultimately being the key tool to estimate future climate (Masson-Delmotte, 2019). The complexity of ESMs has increased with the inclusion of a progressively larger number of GCM components and processes and with an increasing level of realism in representing them. This evolution and the needs for intensive simulation of the climate system at different timescales relies on the progressive increase in computing resources, better physical understanding of climate subsystems and their interactions and model-data comparison, thereby improving quantification of uncertainties and detecting unresolved processes or model biases.

Model simulation of different time intervals in the past

Extending the time interval of simulations to the past well beyond the instrumental period helps to analyze the response to major drivers and feedbacks for past climates outside the range of recent variability, thereby assessing the credibility of climate models used for future climate projections. Ultimately, it helps in disentangling long-term natural variability such as solar or volcanic, from anthropogenic influences i.e. greenhouse gases, land-use-land-cover and associated aerosols, among others. This implies a continuous need for extending the representation of proxy-based external forcing reconstructions as far back as possible (Jungclaus et al., 2017).

- The pre-industrial millennium (*past1000* transient simulations), from 850 CE to 1849 CE is used to investigate the response to (mainly) natural forcing under background conditions not too different from today, and to discriminate between forced and internally generated variability at interannual to centennial timescales. The most complete version of these simulations in terms of the mechanisms considered are the *all-forcing* simulations, incorporating an exhaustive set of natural and anthropogenic processes. Additionally, single forcing simulations are also considered to address the sensitivity to individual radiative forcing factors. Few models have produced a comprehensive set of experiments for both types of *all-* and *single*-forcing ensembles (e.g. and future simulation efforts expand on this line as computing capabilities increase) (Otto-Bliesner et al., 2015).

- Additionally, three more periods are currently targeted that are particularly relevant to provide a context for early human influences (the mid-Holocene, 6,000 years ago; the Last Glacial Maximum, 21,000 years ago and the Last Interglacial, 127,000 years ago). All these periods are considered in equilibrium simulations, keeping forcing values constant and representative of average conditions within the time interval considered. Future challenges will likely incorporate the production of long continuous ESM simulations within them (transient simulations; Otto-Bliesner et al., 2015) and eventually glacial-interglacial transitions, once computational resources and improved forcing representations allow for it.

Advances in model physics

Future simulation efforts will continue to allow for testing our understanding of the interplay between radiative forcing and atmospheric circulation as well as the connections among large-scale and regional climate changes giving rise to phenomena such as polar amplification or monsoon responses. Paleoclimate Modelling Intercomparison Project (PMIP) ESM experiments will be more and more complemented by sensitivity experiments that allow for improving our understanding and quantification of the strength of atmosphere, ocean, cryosphere, and land-surface feedbacks, thus highlighting the role of specific PMIP efforts dealing with model physics and forcing changes, like the Ice Sheet, Couple Climate and Carbon Cycle, or the Aerosol and Chemistry MIPs (Eyring et al., 2016):

- Dynamic vegetation and biogeochemical cycle modelling. Models will have to account for the biogeophysical and chemical influences of land-use and land-cover changes, including more realistic subsurface thermodynamics as well as interactions between subsurface thermodynamics and hydrology of relevance for permafrost and carbon pools (Bonan and Doney, 2018; Melo-Aguilar et al., 2018).

- Understanding aerosol-cloud feedbacks. The current generation of models have to deal with uncertainties in the simulation of the aerosol direct and indirect effects, which produce diverse impacts on the spread of climate sensitivity (Meehl et al., 2020) by modulating the radiative transfer of energy, distributing precipitation and influencing tropical and extratropical circulations. Future model challenges include better knowledge of the role of convection and convective aggregation in cloud feedback, together with sources for the variability of storm tracks and tropical rain belts (Bony et al., 2015).
- Troposphere-stratosphere two-way coupling: Interactions between atmospheric variability, dynamics and climate change represent challenges (Gerber and Manzini, 2016) that address (i) how dynamics contribute to model biases in atmospheric mean state and variability, (ii) what the role of dynamics and the transport of momentum and energy in shaping the climate response to anthropogenic drivers and related uncertainties is, and (iii) how does the stratosphere affect climate variability at intra-seasonal, inter-annual and decadal timescales.

Other issues include a better understanding of the rate of deep ocean energy storage and the connections with modes of internal climate variabilities or the accurate simulation of storm track climatology and variability. Ultimately, future large increments in High Performance Computing resources will allow for boosting model resolution reaching explicit representation of essential processes, avoiding parameterizations of convection and cloud formation and leading to reduction of regional biases (Palmer and Stevens, 2019).

Advances in model-data integration and comparison

Paleoclimate model-data comparison offers powerful tools to test hypotheses about past climates, quantify the limits of knowledge, and design the next generation of modelling and reconstruction efforts (Braconnot et al., 2012). Techniques for comparing and combining numerical models and data (including data assimilation) include metrics for comparison and uncertainty quantification of both climate reconstructions and simulations. Analyses focus on key paleoenvironmental questions including but not limited to assessing climate sensitivity and characterizing internal climate variability, large-scale dynamics and extremes (Fernández-Donado et al., 2013; Luterbacher et al., 2016; PAGES2k Consortium et al., 2017). Analyses span a wide range of proxy systems and time scales and are burdened by uncertainties in both sources of information and the fact that both approaches target conceptually different representation of reality: while climate reconstructions aim to capture the precise evolution of a climate variable in the past, simulations provide estimates that are consistent with the physical equations and with the imposed initial and boundary (forcing) conditions. Therefore comparison approaches must adapt to the specific climate parameter considered and the nature of the proxy information used as observational information. Model-data comparison will benefit from the availability of wider simulation ensembles of a larger time span as discussed in 3.1, as well as from improvements in reconstruction techniques and in their quantification of uncertainties. This will lead to more detection-attribution exercises through which external forcing and specifically human-induced changes can be discerned from natural variability (Hegerl et al., 2011), as well as improved understanding on the role of internal variability and natural forcing on extreme periods that had an impact on society and the demise of civilizations in the past (Steiger et al., 2019). Also, expected progress in the near future incorporates more data-assimilation exercises blending proxy data and model work to nudge model simulations to the observed evolution in proxy data, thus addressing an accurate representation of past internal variability in the targeted parameters and timescales (Bothe and Zorita, 2020).

A complementary approach to model-data comparison is the generation of simulated surrogates for proxy data using forward models applied to climate model output, thus simulating directly proxy variables suitable for comparison instead of climate variables. The development of such specific modelling using offline forward models can produce a more accurate characterization of the evolution of specific subsystems in the past, with applications also in future climate change scenario simulations. Some examples are ice sheet modelling, tree growth, water isotope-based proxies or subsurface temperatures (Melo-Aguilar et al., 2020).

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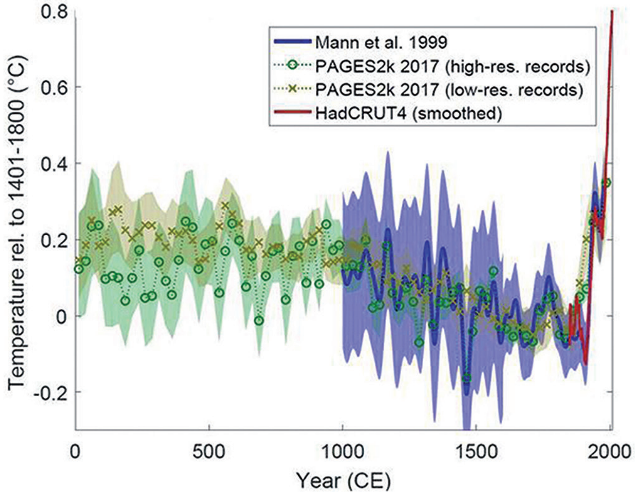
ACADEMIC SLIDE

Past Global Changes: a context to the Anthropocene

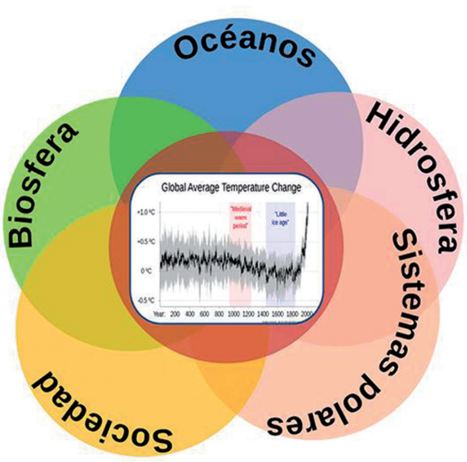


Reconstruction of past temperature variations for last 2000 years based on different natural archives such as ice cores, lake and marine sediments, speleothems, corals, tree-rings and pollen records

Emile-Geay et al., (2017)

DISSEMINATION SLIDE

Cambios Globales Pasados: un contexto para el Antropoceno



- Los cambios globales de los últimos 2000 se han debido a la interacción entre forzamientos naturales y antrópicos.
- Caracterizar los cambios globales de los últimos 2000 años.
- Definir sus impactos en la sociedad, hidrología, océanos, sistemas polares y biosfera.
- Modelizar los cambios globales del pasado para separar los mecanismos de forzamiento.

CHALLENGE 2

ABSTRACT

Climate change is one of the main threats for our planet, but there are still remarkable knowledge gaps and uncertainties. Further studies are thus required to establish a robust and comprehensive assessment of climate change and variability. Current challenges in Climate Science are: i) evaluation of the climate change with a focus on data rescue and analysis to better contextualize current anthropogenic forcing and natural climate variability; ii) assessment of physical processes, including feedbacks between thermodynamics and dynamics, and interactions between the Earth System components; iii) monitoring and forecasting of extreme events, which account for the largest socio-economic and environmental losses associated to climate change; iv) analyses of future changes at global and regional scales; and v) provision of reliable and transparent climate services to user communities. Advances in a better understanding of the processes and mechanisms of climate change should guide the design and implementation of mitigation and adaptation strategies and policy, which will alleviate and improve future human life on earth.

KEYWORDS

climate change | climate variability | circulation mechanisms | climate extremes | climate services | climate modelling

CHALLENGE 2

CLIMATE CHANGE PROCESSES, MECHANISMS AND FUTURE SCENARIOS.

THE BASIS TO DEVELOP CLIMATE SERVICES AND TO IMPROVE ENVIRONMENTAL AND SOCIETAL ADAPTATION

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1. INTRODUCTION AND GENERAL DESCRIPTION

Nowadays, climate change is one of the main threats to our planet. Human activities, in particular the increased atmospheric concentrations of greenhouse gasses, have altered the global energy balance. The most noticeable consequence has been the increase of the near-surface temperature at the rate of 0.1 ºC/decade over the last century (Intergovernmental Panel on Climate Change, 2014). There are multiple consequences of this global warming, with countless socio-economic and environmental costs such as sea-level rise, polar and mountain glaciers melting, snow cover retreat, more frequent land and marine heatwaves, changes in animal and vegetation phenology and more severe forest fires. The fingerprints of anthropogenic climate change are complex, involving spatial variations related to regional processes and superposition with the non-linear natural variability of the climate system. Therefore, there are still remarkable knowledge gaps and uncertainties, and further studies are required to establish a robust and comprehensive assessment of climate change and climate variability. Uncertainties affect mostly dynamical aspects in all components of the Earth System, and their effects on the energy and water cycles. These uncertainties directly affect the robustness of future climate projections. They also affect our capability to forecast extreme events accurately (e.g., tropical and extratropical cyclones, droughts, among others), which have considerable hydrometeorological implications and severe socio-economic and environmental impacts. The assessment, understanding and attribution of climate change is the first mandatory step to deal with a large number of impact-related processes framed under the concept of global change (e.g., impacts in biodiversity and primary production), since climate is the principal driver of these processes.

To bridge these gaps and reduce uncertainties, it is necessary to better quantify the rates of change in all physical components, for a range of spatial and temporal scales. This first challenge must consider a variety of climate elements (i.e. not only air temperature and precipitation), with focus on the rescue and analysis of available historical observations and proxy records to better contextualize and discriminate natural climate variability and the current anthropogenic forcing. This research niche is of high priority for under-sampled and historically inaccessible sites such as polar regions (Challenge 5), deep oceans (Thematic 13), upper atmosphere (Challenge 3 in Thematic 12) or mountain areas, where climate conditions are highly variable in space and time, and very sensitive to changes in the radiative forcing. The assessment of physical processes, including feedbacks between thermodynamics and dynamics, and interactions between the Earth System components (land-atmosphere-ocean-ice coupling) is a second priority in order to understand the past evolution of the climate system, constrain the range of natural variability and quantify its responses to anthropogenic forcings. The third priority aims at quantifying the observed changes and covers the triggering factors of extreme events, which are still challenging to identify, monitor and forecast. A fourth challenge refers to the uncertainties of climate projections and the need for constraining future changes at global and regional scales in support of more efficient mitigation and adaptation strategies. The latter requires the implementation of sophisticated computational resources, improved representation of processes and the development of more comprehensive global and regional Earth System models with higher spatial resolution. Finally, the last challenge concerns a timely provision of reliable and transparent climate services to user communities, since many economic and social activities, as well as policy decisions, depend on the availability of accurate climate information, including long-term climatologies, monitoring systems, forecasts (from days to decades) and long-term projections. This information must be summarized in customized climate products and services to fit the needs of end-users, therefore requiring end-to-end engagement from the implicated actors.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

In recent decades, enormous effort and resources have been invested in monitoring climate evolution and providing scientific evidence of the anthropogenic origin of the ongoing climate change. The vast body of science generated (Intergovernmental Panel on Climate Change, 2014), the sustained warming of the globe and the increasing occurrence of extremes (Sillmann *et al.*, 2017) have shifted the perception of society and decision-makers from scepticism to a majority acceptance of the anthropogenic origin of climate change. The signing of the Paris agreement in 2015 (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement; last accessed 1 August 2020) is perhaps the main milestone in this transformation because, despite the actual level of commitment, most governments recognized the human role in climate change. Simultaneously, the efforts in observing the Earth System are higher than ever, with an observing and modelling capacity able to generate petabytes of data, most of them freely accessible. This availability of data opens the road to a new stage for climate scientists.

As we move into an unknown warmer World, new questions arise that need to be addressed while filling critical gaps in the current state of basic science. Understanding and quantifying changes at regional and local scales in the unequivocal warmer world is perhaps the main scientific challenge ahead due to the complex dynamics and interactions of the major components of the climate system. The massive data available, jointly with the increasing computing facilities derived from the development of high-performance computers and cloud computing services, pave the way to cope with this challenge and allows including new disciplines into the climate sciences. The combination of earth physics and chemistry, data science and soft computing techniques (Thematic 11) may be a fundamental tool in this context.

Climate is one of the key elements defining the ecological ceiling of human wellbeing (Raworth, 2017), and it impacts socio-economic sectors including health, energy, agriculture, infrastructures and economy (National Academy of Sciences, 2019). The improvement of comprehensive observing and modelling systems has allowed climate scientists to provide climate services (Street, 2016). The advances derived from a better understanding of the processes and mechanisms of climate change at different scales will also increase the added value of these services. Once the society has fully acknowledged climate change, mitigation and adaptation policies represent the basis for integrating the climate dimension into decision- making processes. Advanced climate science can now contribute to guide the ecological transition to a greener economy and the achievement of Sustainable Development Goals (SDGs). For instance, the recovery from the devastating economic repercussions of the COVID-19 pandemic can be a chance to improve the interactions between climate and economy. The recent FEDEA report (*Fundación de Estudios De Economía Aplicada*; https://www.fedea.net/quinto-informe-del-gmtc-porunaeconomia-competitiva-verdey-digital-tras-el-covid-19/) considers that the foreseen European Fund for Reconstruction will be mostly based on the Objectives of the European Green Deal and the Digital strategy. Projects contributing to decarbonization and climate change fight should be a priority since they can stimulate economic activity with a long-term impact on attaining sustainable growth. To this end, governments and research agencies must invest more funds in climate observation and the evaluation of climate change and climate variability. Only sustained funding support can cope with the increasing demand for better climate science and services.

The specific challenges described below are well aligned with the United Nations SDG 13: Climate action. As climate science sets the grounds of climate change and provides projections for the development of adaptation and mitigation strategies, and the quantification of impacts, these challenges are also relevant for other SDGs, such as SDG 3: Good Health and Well-being; SDG4: Clean water and sanitation; SDG 7: Affordable and Clean Energy; SDG 11: Sustainable cities and communities; SDGs 14 (Life below water); and 15 (Life on land).

3. KEY CHALLENGING POINTS

3.1. Evaluation of climate change at different spatial and temporal scales

Climate research has brought increasing levels of public awareness and policy commitment on climate change since the 1990s (e.g., Earth Summit, Rio Janeiro, 1992), and climate change is now acknowledged as a major environmental issue for the society. During these three decades, there have been considerable achievements in the evaluation of past climate variability and trends at different spatio-temporal scales, as summarized by the quasi-periodic Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC 1990, 1996, 2001, 2007 and 2013). The main conclusion of its Fifth Assessment Report (Intergovernmental Panel on Climate Change, 2014) is that contemporary warming of the land and ocean is unequivocal (e.g., the past five years are the warmest on record, and, since the 1980s, each successive decade has been warmer than any preceding one of the 1850-2019 period), and primarily caused by anthropogenic emissions of greenhouse gases. However, the non-linearity of the climate system, the limited availability of climate records over large regions (e.g., Southern Hemisphere, polar regions, the Tibetan Plateau –known as the "Third Pole Region" –), and the representation of small-scale processes and internal variability in climate models make the detection and attribution of climate change a big challenge (Otto *et al.*, 2016). Figure 1 outlines the state-of-the-art in climate change and climate variability, and critical challenges that require future in-depth investigations to improve our understanding of the climate system.

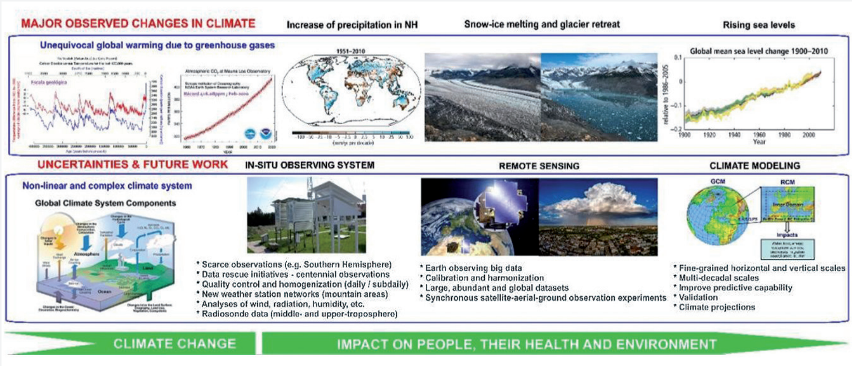
In particular, comprehensive climate studies are needed to understand physical processes better (see section 3.2), move forward in the detection and prediction of extreme events (section 3.3) and improve the realism of climate models (section 3.4). As in these issues, the assessment of climate change relies on observational data collected from in-situ networks, satellite observing systems and indirect proxy records, as well as on physically consistent data simulated by models of diverse complexity, some of them assimilating observations. Accurate and homogeneous long-term observational records are still crucial to quantify the observed changes over the industrial period. In particular, data rescue initiatives (e.g. from books or documentary sources available at weather archives in the National Weather Services and libraries) are strongly needed over under-sampled regions where surface, sub-surface and upper-air climate information exists such as developing countries, the Southern

Hemisphere or the Pacific Ocean. Long-term series based on terrestrial and marine observations before the 1960s represent valuable sources to fill the gaps, improve the characterization of climate variability at decadal timescales and assess with more confidence the observed changes. For example, the Copernicus Climate Change Service (C3S), the Atmospheric Circulation over the Earth (ACRE), or the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) are international initiatives promoting and supporting the rescue, digitization and harmonization of documented instrumental data records, underpinning 3D weather reconstructions (reanalyses) spanning the last 250 years (Slivinski *et al.*, 2019). For the assessment of past climate changes further back in time, the reader is referred to Challenge 1 in this Thematic.

The development of high-quality networks for climate monitoring in, e.g. mountain areas, the Arctic and Antarctic regions, and the maintenance of long-term observing systems is also a priority. Thus, international initiatives are required to support the continuity of existing analogical observational networks, which represent the fundamental pillars of climate change assessments. Moreover, the improvement of algorithms to advance in the quality of data at finer temporal resolutions (i.e., daily and sub-daily data) is mandatory. The detection and attribution of trends in climate extremes requires at least daily resolution, and some weather phenomena, such as daily peak wind gusts, are even more demanding (resolution of the order of seconds). However, long-term time series (>30-years) at this resolution are still scarce, since these measurements started with the automatization (data-logging) of the observational network in the mid-1980s. The main goal for the assessment of climate change and variability is combining the assimilation of ground-based observations (e.g., air temperature, precipitation, wind speed) with the calibration-harmonization of satellite (e.g. clouds, aerosols) data in a comprehensive way, and reduce biases and inhomogeneities in the current generations of reanalysis. These products also have benefits for the evaluation of models employed for climate projections and operational forecasts.

Most studies on climate change and variability have focused on air temperature and precipitation and their related extremes (heat/cold waves, droughts, heavy precipitation events and floods), while other variables have only been investigated in recent years. Alternative power sector decarbonization strategies demand comprehensive climate studies of changes in other atmospheric parameters such as wind speed (stilling *vs* reversal; Zeng *et al.*, 2019), solar radiation (dimming *vs* brightening), relative humidity or evaporation. There

FIGURE 1–Overview of observed climate trends, uncertainties and future work.



is also a limited understanding of climate variability and change in the middle and upper troposphere, as well as in other components of the climate system (ocean, land and ice; e.g. Challenges 2 and 6 in Thematic 13), which are major carbon sinks and significant contributors to the long-term responses to climate change. It is therefore critical to effectively analyze different climate datasets in order to evaluate the real dimension of the ongoing climate change at different spatial (from local-mesoscale to hemispheric-global) and temporal (from sub-daily to multidecadal) scales, and quantify the role of anthropogenic factors. The latter requires a better characterization of climate responses to external natural forcings (e.g. Challenge 3 in Thematic 12) and internal variability, which ultimately relies on a better understanding of past global changes from improved proxy reconstructions and models (Challenge 1). The scientific leitmotiv is "knowing the past climate to understand the present climate change and better predict climate projections needed for climate change adaptation".

3.2. Physical mechanisms of climate change processes

Global warming processes are consistent with a thermodynamic response to anthropogenic forcing. Therefore, achieving the global targets established by the Paris agreement will depend on human decisions, i.e. the pathway of greenhouse gasses emissions. Regarding physical aspects of global climate change, the indirect effects of aerosols and cloud feedbacks are the primary sources of uncertainty in radiative forcing and climate sensitivity, respectively (Bony *et al.*, 2015).

External forcings with large spatial variations (e.g. anthropogenic aerosols), regional forcing (e.g. land-cover changes) and regional-scale cloud, vegetation or snow cover feedbacks cause spatial departures from the global warming response (Figure 2). At regional scales, there is a need for a better understanding and quantification of these feedbacks and improved model implementation of atmosphere-ocean-land-ice interactions (Roe *et al.*, 2015). For example, the relative roles of cloud, water vapour, sea ice and snow feedbacks in Polar amplification or, similarly, the influence of vegetation dynamics and subsurface processes in land-atmosphere coupling over transitional regions, are poorly understood, scarcely measured and underrepresented in climate models. Some of these processes show multiple equilibrium states and irreversible transitions that can be represented by hysteresis cycles. Specifically, characterizing feedbacks and hysteresis is a priority for the understanding of abrupt and irreversible changes if critical thresholds are transgressed ('tipping elements'; Lenton *et al.*, 2008), e.g. the collapse of the Atlantic Meridional Overturning Circulation (AMOC), Amazon dieback, instability of ice-sheets.

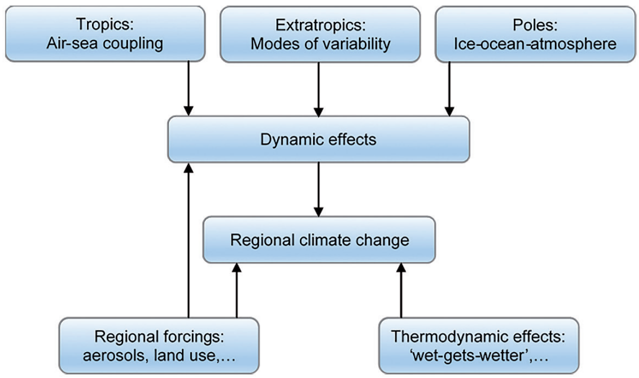
At scales from global to regional, the climate is also strongly affected by dynamics, such as monsoons, storm tracks and planetary-scale waves in the atmosphere, tropical waves, ocean convection, currents and large-scale energy transport in the ocean, or ice fluxes in the cryosphere (Figure 2). In contrast to thermodynamics, dynamical responses to natural (see Challenge 3 in Thematic 12) and anthropogenic forcings are often not robust in observations or models, leading to low confidence in past or future changes in related variables (e.g. precipitation, drought; Shepherd, 2014). Dynamical changes can counteract global warming- induced increases in water vapour, and cause regional precipitation departures from the expected thermodynamic response (i.e. the 'wet-gets-wetter, dry-gets-drier' pattern; Xie *et al.*, 2015). For example, circulation trends have dominated over thermodynamic changes in the summer Asian monsoon, causing rainfall decreases over the 20th century, and future precipitation changes in some mid-latitude areas depend on the magnitude of the projected slowdown and poleward expansion of the Hadley circulation.

In polar regions, marine and terrestrial ice fluxes, and their interactions with the atmosphere and ocean govern the dynamics of the ice-sheets and are important sources of uncertainty for global sea level rise (Challenge 6, Thematic 13). In the equatorial and tropical regions, the atmospheric circulation is coupled with Sea Surface Temperature (SST) anomalies, as in El Niño-Southern Oscillation (ENSO), and so are their changes. However, observations and models do not show robust forced responses in this and other tropical phenomena (Intergovernmental Panel on Climate Change, 2014). Therein, the governing processes are thought to involve delicate balances between opposite feedbacks modulated by the background state. Therefore, improving observations and reducing model biases in the mean state (e.g., the double Inter-Tropical Convergence Zone, ITCZ) is expected to bring an understanding of regional processes, tropical-extratropical interactions and their responses to climate change. Small-scale processes such as clouds, wind gusts, convection or gravity waves, are unresolved (parameterized) in global and even regional climate models, highlighting the need of collaboration between the weather and climate communities, as well as increases in resolution and physical details (Palmer and Stevens, 2019).

In the extratropics, where internal variability is large, observed trends and climate change responses in atmospheric circulation are comparatively smaller, with a tendency to project onto modes of internal variability (Intergovernmental Panel on Climate Change, 2014). Therefore, distinguishing the forced signal from 'climate noise' represents a major challenge (Figure 2). Although internal variability is more considerable on smaller spatial scales, decadal modes of SST variability and interactions between ocean basins may favour temporary global warming hiatus (Collins *et al.*, 2018). However, this low-frequency variability is poorly characterized due to the limited length, coverage and quality of instrumental records. Blended approaches combining paleoclimate reconstructions and modelling (Challenge 1) as well as new reanalyses with coupled assimilation of ocean and atmospheric data are promising tools to constrain internal variability, with implications for mechanistic understanding, model evaluation and climate change attribution.

Increasing computational resources has allowed large ensembles of model simulations accounting for internal variability and a better assessment of forced signals and associated mechanisms. However, the spread of simulated responses across global and regional models (model uncertainty) is large, sometimes involving opposite changes (Shepherd, 2014). Unlike internal variability, model structural uncertainty should be reducible by improving our computational capabilities and understanding of the Earth system components and their interactions. Despite their increased comprehensiveness and realism in the representation of small-scale processes, the robustness of

FIGURE 2–Physical origins of regional climate change (adapted from Xie et al., 2015).



climate projections at regional scales has improved little in recent years, pointing at pervasive problems in fundamental processes through model generations (Collins *et al.*, 2018). Earth System models of very high resolution capable of simulating storms, convection, mesoscale ocean eddies and relevant land-atmosphere interactions will allow an explicit representation of essential processes. As a result, a reduction of systematic biases in current models is expected (Palmer and Stevens, 2019). The development of this new model generation should be sustained, multinational, and coordinated to achieve the necessary level of high-performance computing and information technology. In the meantime, approaches to understand model uncertainty are emerging and inform on relevant mechanisms of climate change. They include the use of a hierarchy of models of diverse complexity, pacemaker experiments with partial coupling or 'storylines' (Collins *et al.*, 2018). These frameworks have shown that some uncertain projections arise from competing influences (so-called 'tug-of-war') of climate change responses across the multi-model ensemble (Shaw *et al.*, 2016). Future progress depends on mapping these drivers of regional climate change (e.g. the stratospheric polar vortex).

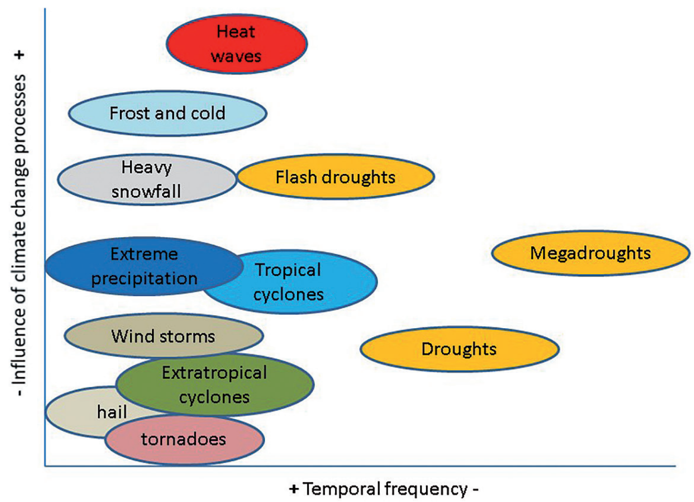
In summary, uncovering the governing processes of climate change poses a range of challenges in terms of the observational record, physical understanding and model simulations. Priority research questions for the next years range from the quantification of feedbacks, the role of small-scale processes (and model parameterizations), the characterization of internal variability or the development of theoretical grounds for the dynamical mechanisms of climate change. Advances in any of them will ultimately require moving forward in the physical understanding of dynamical aspects of the atmosphere, ocean, land and ice subsystems, and their interactions, as well in our capabilities to simulate them.

3.3. Extreme events

Climate extreme events involve complex processes and multiple factors causing unusual values of a climate quantity. Extremes of greater concern are related with air temperature (e.g. frost days, cold spells, heatwaves), precipitation (e.g. heavy rainfall and snowfall events, hail, droughts), wind (e.g. extreme wind, tornadoes) or specific weather systems (e.g. tropical and extratropical cyclones). The assessment of some of these extremes is challenging given the limited availability of long observational records, e.g. for hail, snowfall or tornadoes (Seneviratne *et al.*, 2012). Different spatio-temporal scales characterize extreme events, and the evidence of anthropogenic influences also varies among them (Figure 3). The attribution of specific extremes to climate change is currently a major priority (Trenberth *et al.*, 2015), but still challenging for some types of extremes (e.g. those unrelated to air temperature or occurring at small spatial scales), given model limitations and uncertainties, and short observational records (Paciorek *et al.*, 2018). As extremes are intrinsic to the climate system, they are also influenced by natural variability. Therefore, historical data rescue initiatives, including the development of proxies is pivotal to characterize the influence of natural variability in the occurrence and intensity of extremes and to advance in the detection of trends attributable to anthropogenic factors. An additional common challenge to all types of extremes is the improved prediction, particularly at sub-seasonal-to-decadal (S2S) time scales, i.e. from 10 days to three months (see also Challenge 3 in Thematic 12). Relevant issues include the need of sustained observation and advanced data assimilation, understanding and representation of physical processes with predictive skill, the initialization, coupling and ensemble size of forecast systems, the quantification of uncertainties, and the correction or reduction of model imperfections and drifts (including the signal-to-noise paradox).

Some evidence suggests that some extremes are becoming more frequent, persistent or severe because of anthropogenic climate change. This is

FIGURE 3–Temporal frequency of different types of extreme climate events and the influence of climate change processes



particularly evident for temperature-related extremes such as heat waves (e.g. Barriopedro et al., 2011). Despite this, the understanding of thermodynamical and dynamical influences and their interactions in the severity and persistence of heatwaves is still limited. While there is general agreement on the type of weather systems promoting heatwaves, the relative importance of the involved physical mechanisms (e.g. warm advection *vs* adiabatic processes) remains poorly understood, as well as their future changes. When combined with antecedent dry conditions persistent high- pressure systems have shown to amplify air temperature anomalies during major European heatwaves, and even instigate extreme conditions in surrounding regions (self-propagation; Miralles *et al.*, 2014). However, there are large uncertainties in the magnitude of this land- atmosphere coupling and its importance for heatwaves in other regions and under future climate conditions. Other potential precursors (e.g. anomalies in sea surface temperatures) remain less explored.

Differently, climate dynamics largely drive other extreme events. For example, depending on the region, extreme precipitation is triggered by extratropical depressions, tropical cyclones, convective systems or upper-level cut-off lows, which frequently cause severe floods, large socio-economic impacts and sometimes human causalities. However, observed trends in extreme precipitation are often uncertain, and in some regions (e.g. the Mediterranean) model projections do not even agree on the sign of future changes (Intergovernmental Panel on Climate Change, 2014). Developing long-term and homogeneous time series of weather extremes and advancing on the understanding of the atmospheric circulation responses to climate change are the main challenges to advance on these issues. Moreover, it is necessary to move towards a sub-daily characterization of these extremes, which is the most relevant timescale to quantify their severity and associated impacts. Similarly, the assessment of changes in wind-related extremes is also hampered by intrinsic difficulties to measure wind and by the quality and temporal homogeneity of wind observations. These limitations in the observational record also pose challenges to the development of statistical models capable of reproducing the tails of the distribution or the spatial mapping of these extremes.

Droughts are among the most complex and hazardous extreme events, with noticeable agricultural, hydrological, environmental and socio-economic consequences (Wilhite and Pulwarty, 2017). There is considerable uncertainty in the magnitude of drought trends, both globally and for many regions. Available instrumental records of precipitation-based drought indices do not reveal significant drying trends globally (since at least the 1950s; Spinoni *et al.*, 2019). However, warming of the atmosphere by human-made climate change can affect drought severity by increasing the atmospheric evaporative demand (AED). The uncertainties associated with future climate change projections in drought severity are also large. Major issues concern the relative role of radiative forcing *vs* vegetation fertilizing CO_2 effects (Vicente-Serrano *et al.*, 2020a), the complex processes affecting AED and its varying importance across drought types, and the choice of metrics for drought quantification (Vicente-Serrano *et al.*, 2020b). Progress requires an improved representation of eco- physiological processes in the current generation of Earth System Models. Besides, there is an urgent need for accurate and long-term available measurements of soil moisture and actual evapotranspiration, which are poorly sampled and understood.

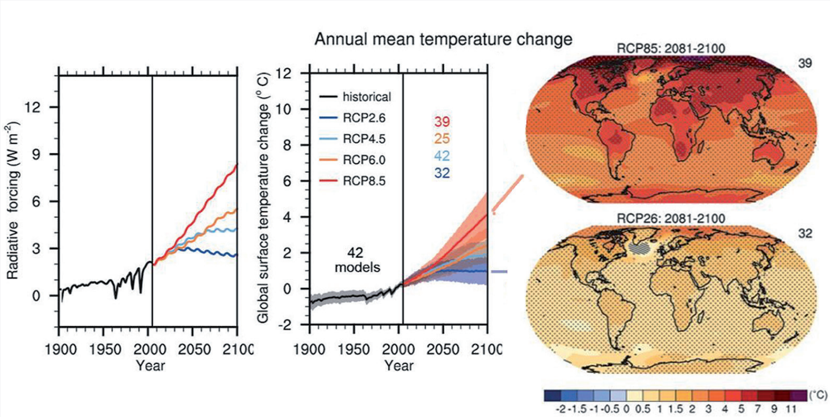
Some of the extreme events in Figure 3 are also the principal triggers of other hazards (see Challenge 3 in Thematic 14). For example, extreme precipitation and severe storms are responsible for flash floods affecting urban areas and river catchments, landslides, soil erosion and other geomorphological hazards. Advances rely on improvements in the identification and monitoring of relevant processes, their representation in impact models and the assembly of the latter with climate models. Similarly, droughts are a leading factor of forest fires, along with extreme heat, low relative humidity and gusty winds, and assessing the relative roles and interactions of these factors and implementing them in forest fire risk models is also a priority (Turco *et al.*, 2018). There are also pressing needs to develop end-to-end attribution studies of extreme events that quantify the human contribution to changing risks in the associated impacts of extreme events, which requires cross-disciplinary development.

Human and natural systems are particularly vulnerable to compound events (a combination of events, not necessarily extremes, that lead to significant impacts) or to concurrent climate extremes (i.e., multiple extremes of the same or different type occurring at the same time or in sequence at either the same place or at remotely-linked locations). In recent years, these events have received considerable attention (Zscheischler *et al.*, 2018), since they have disproportionate impacts through additive or even multiplicative effects. A complex chain of effects are usually in the origin of compound and concurrent events, e.g. mutually reinforcing cycles, which are still poorly diagnosed and understood. The best-known example is the relationship between droughts and heatwaves, or the simultaneous occurrence of heatwaves in remote regions of the same hemisphere. However, the state of knowledge of these events is at its infancy. Understanding the interaction of processes associated with different types of extremes is mandatory to characterize the physical drivers better and improve the predictive skill of current models regarding these events.

3.4. Future projections

Climate change impact, adaptation and mitigation research and policymaking require information on the foreseeable long-term (century time scale) projection of the climate (typically along the 21st century). Global Climate Models (GCMs) are the primary source for this information. GCMs simulate numerically the global dynamics of the climate system components (atmosphere, hydrosphere, cryosphere, land, and biosphere), as well as the physical and biochemical interactions between them. This includes the energy and water cycles, as well as biogeochemical cycles (Challenge 3) in the case of Earth System Models (ESMs). These simulations are computed over global grids with prescribed resolution (typically hundreds of kilometres and sub-daily time steps)

FIGURE 4—Historical and future (for different scenarios, in colours) radiative forcing (left) and resulting global air temperature change (middle, w.r.t. the 1981-2000 reference period) as simulated by the CMIP5 multi-model ensemble (spread around the solid lines, which represent the multi-model mean). The spatial patterns for the end of the century (2081-2100) for high- and low-end emission scenarios are shown in the right panels Credits: Adapted from Intergovernmental Panel on Climate Change (2014).



considering alternative scenarios as plausible future pathways for socio-economic factors (such as world population growth, economic development and technological progress) and climate and mitigation policies (Shared Socio-economic Pathways, SSP). The scenarios account for the range of inherent uncertainty associated with human decisions and result in different trajectories of greenhouse gases concentrations and radiative forcing for the climate system (Representative Concentration Pathways, RCPs) encompassing low, medium and high emissions (typically RCP2.6, RCP4.5 and RCP8.5, respectively) with the corresponding ensemble of climate change projections (Figure 4).

Although the most considerable uncertainties in future climate projections stem from human actions (scenario uncertainty, Figure 4), there are also model-related uncertainties affecting the climate projections for a given scenario. These are associated with intrinsic limitations and imperfections of GCMs such as the limited spatial resolution (e.g. hampering the explicit resolution of cloud physics, which are parameterized); an incomplete understanding of Earth system components (e.g. dynamic ice sheet processes) and their interactions (e.g. land- atmosphere feedbacks; Seneviratne *et al.*, 2010); and missing processes (e.g. plant physiology; Brodribb *et al.*, 2020). The reduction of these model uncertainties is currently a priority in order to constrain climate projections and better inform adaption. This has fostered continuous model improvement in both complexity (from the initial atmosphere-ocean coupled models to the current Earth System Models, ESMs) and spatial resolution. Therefore, supporting the continuous validation and improvement of GCMs is a critical task for the credibility of model results and the confidence in climate projections. This, in turn, requires sustained technological development, investment on high-performance computing facilities and international collaborative effort. Ensembles of different models are used to sample structural model uncertainty, with each model providing climate projections under the same forcing conditions (multi-model ensemble; shading in Figure 4). Selecting the subset of models that better resemble the magnitude and trends in observations as a way to constrain future projections has been questioned (Herrera-Estrada and Sheffield, 2017). Alternative approaches are emerging and include weighting models according to each model's ability to reproduce observations using either empirical relationships (emergent constraints) or process- based frameworks (e.g. Bayesian techniques with perturbed model parameters; Xie *et al.*, 2015).

Model projections are also affected by internal variability (climate 'noise' from natural processes in the coupled system). Different to model formulation, internal variability is largely irreducible (as it is an intrinsic property of the system) and its uncertainty tends to dominate near-term projections at continental scales (e.g. up to half of the mid-century multi- model spread over North America or Europe). This means that climate projections must be probabilistic, especially at regional and decadal scales, which represents a challenge for climate change communication (Deser *et al.*, 2020). The uncertainty from internal variability can be sampled from a large ensemble of initially-perturbed simulations with a single climate model under a particular scenario. Important challenges concern the initialization process, the quantification of internal variability and its contribution to climate projections, or the ensemble size, which may require up to ~102 members, depending on the climate field, region, spatio-temporal scale and time horizon. These large ensembles are challenging in terms of high-performance computing facilities, long-term storage, data distribution and access, requiring technological development and big data management (Thematic 11).

Although GCMs are the primary tools used to generate climate predictions, they have limitations to assess climate change impacts at small spatial scales due to their limited resolution (typically 100-200 km). These limitations make strongly necessary to develop and improve methodologies to generate accurate information for climate change projections at local to regional scale. Generally, two main downscaling approaches have been established to bridge the gap between the coarse-scale information provided by GCMs and the regional/local climate information required for climate impact studies (Christensen *et al.*, 2008). On the one hand, dynamical downscaling is based on the use of Regional Climate Models (RCMs) to simulate the climate over a limited region of interest (e.g. Europe) driven at the boundaries by a GCM. RCMs include an improved representation of small-scale processes since they are run at high resolutions (typically 10-50 km). Dynamical downscaling activities are organized by the Coordinated Regional Climate Downscaling Experiment (CORDEX; Gutowski *et al.*, 2016) over fourteen domains worldwide (typically at 44 km resolution, but higher in some domains, e.g. 11 km in Europe). These simulations are done in coordination with the Coupled Model Intercomparison Project (CMIP, https://www.wcrp-climate.org/wgcm-cmip) and provide an additional regional dataset with higher resolution to analyze regional climate change. Despite their higher resolution and improved representation of processes, the added value of RCMs for regional climate changes is not apparent and further research is needed to properly assess the particular merits, benefits and uncertainty of the global and regional components. Given the rapidly increasing spatial resolution of global models (e.g. HigResMIP), it has been argued that RCMs may no longer be required in the coming years, so there is a pressing need for the development of more comprehensive (e.g. atmosphere-ocean coupled, convection-permitting) RCMs.

On the other hand, empirical/statistical downscaling is based on statistical transfer functions linking global circulation predictors (given by the GCMs) to local variables of interest. These empirical functions, which range from simple bias adjustment algorithms to more complex prognosis methods, are learned from historical data using both model outputs and observations. Statistical downscaling is typically applied over small areas and not at a continental scale, but there are ongoing collaborations to compare and produce CORDEX-like projections with these methods (e.g. the VALUE initiative; Maraun *et al.*, 2015). Major issues concern the lack of physical grounds in the statistical relationships, the questioned ability of some statistical techniques to extrapolate values out of its historical range from which they were trained, and other implicit assumptions (e.g. stationarity of the statistical relationships).

Current challenges involve the development of more sophisticated techniques that can account for broader domains and complex non-stationary spatiotemporal linkages, including machine learning techniques [e.g. deep neural networks; Baño-Medina *et al.* (2020); Thematic 11].

3.5. Climate services

The impacts and adaptation community widely use climate change projections (both global and regional), so communicating credibility, limitations and uncertainty in a comprehensive form is crucial for impact and adaptation studies and for informing the decision-making processes and policymaking. Climate services play a key role in this process since they develop actionable sectoral products to meet the particular requirements of the sectoral applications and considering the end-to-end role of uncertainty for the particular application.

Climate services rely on climate data, and hence the first challenge is technological, related to needs that can cope with the exponential growth of data generation, storage and dissemination (see also Thematic 11). This, in turn, requires a sustained international collaborative effort for the development and implementation of standardized methodological approaches. For example, ensembles of multi-model global climate projections are periodically produced (in cycles of approximately 5 years) in the framework of international coordinated experiments such as the CMIP, informing the IPCC Assessment Reports (https://www.ipcc.ch). The latest CMIP6 has contributions of over 40 modelling centres all around the world, resulting in a massive dataset of hundreds of petabytes (Eyring *et al.*, 2016). This information is stored using a federated system (the Earth System Grid Federation, ESGF) which is a crucial international infrastructure providing long term archival and open access to CMIP results.

A second challenge is to translate climate information to policymakers and end-users. This requires the engagement of interested sectors and the resource to multidisciplinary approaches for co-development of useable products. Climate and data scientists must engage with relevant sectoral users and stakeholders that meet the specific requirements of particular applications (e.g. climate impacts in crop yields, as part of the climate services portfolio for agriculture). This is an emerging field that has witnessed an explosion of several international and national initiatives. The best example is the Global Framework for Climate Services (GFCS) (https://gfcs.wmo.int/), promoted by the World Meteorological Organization (WMO) for the development of actionable sectoral products and tools that support and facilitate the use of climate information in specific sectors (e.g. agriculture, energy, hydrology,

FIGURE 5–. COPERNICUS services, including a climate change service providing transparent access to several data sources (satellite, in-situ and model data) to develop sectoral climate services (some end-to-end sectoral services and demonstrators are provided for several sectors). Adapted from https://www.copernicus.eu

biodiversity). The creation of the GFCS has boosted the development of a large number of data portals, frameworks and data services implementing different types of climate services, from generic to sectoral, for different temporal horizons (monitoring, seasonal prediction, climate change projections) and with different user co-development and engagement (Hewitson *et al.*, 2017). An example of generic climate service is the flagship European COPERNICUS programme (Figure 5) operated by different European institutions (ECMWF for climate) in collaboration with groups, companies and institutions from different sectors. COPERNICUS has developed proofs of concepts and demonstrators of generic climate services in several sectors (coastal areas, infrastructure, health, agriculture, insurance, tourism, water management, energy; https://climate.copernicus.eu/sectoral-impacts) and is leading the research and development of climate services in Europe (and worldwide). An example of sectoral service is the FAO Modelling system for agricultural impact of climate change (MOSAICC, http://www.fao.org/in-action/mosaicc) which allows running impact models (hydrology and crop models) driven by climate change data to deliver tailored information on crop production calibrated for the region of interest. A big challenge in this field is the distillation of different (potentially conflicting) lines of evidence (e.g. global and regional climate projections) providing actionable regional information characterizing the different sources of uncertainty [an initial work shows the complexity of this task; (Fernández *et al.*, 2019)]. A technical challenge is that the delivered product must be tailored to the specific user' needs and may not be transferrable to other regions or users of the same sector, therefore requiring a dedicated development.

At a national level, the Spanish national Meteorological Agency (AEMET; http://www.aemet.es/) provides basic climate data services for all temporal scales via its open data service (https://opendata.aemet.es) and collaborates with research groups (including CSIC) to provide sectoral services for relevant national issues (e.g. for drought monitoring). The Spanish Plan for Adaptation to Climate Change (PNACC) also supports initiatives for gathering and harmonizing existing projections (e.g. from CMIP5 and CORDEX) and generating new ones focusing on PNACC applications (Fernández, 2017). For example, the PNACC scenario portal (https://escenarios.adaptecca.es) provides visual and numeric harmonized regional climate projections for essential climate variables and generic derived indices. Notwithstanding these national efforts, there is a lack of a national structure coordinating individual initiatives and services and connecting them with users and stakeholders so they can participate in the co-development of the products.

Besides seasonal forecasts and climate change projections, climate services also deal with real-time monitoring systems. There are climate phenomena for which the forecasting skill is minimal, but monitoring is highly reliable and can provide useful early warning information if the climate phenomenon evolves slowly. An example of the latter is drought monitoring systems (https://monitordesequia.csic.es/monitor), which provide synthetic comprehensible information on the spatial extent of droughts based on climate drought indices that can be translated to different types of impacts (https://droughtmonitor.unl.edu). Drought monitoring systems adapted to defined user requirements need to be developed (e.g. monitoring for specific crops cultivations, better spatial resolution and temporal frequency). An essential issue will be to link drought monitoring information with specific impacts to translate the synthetic climate information to real uses. The development of similar climate services for other climate-related extremes is challenging and underexploited, mainly if they involve non- meteorological factors (e.g., social and land-use factors for wildfire risk).

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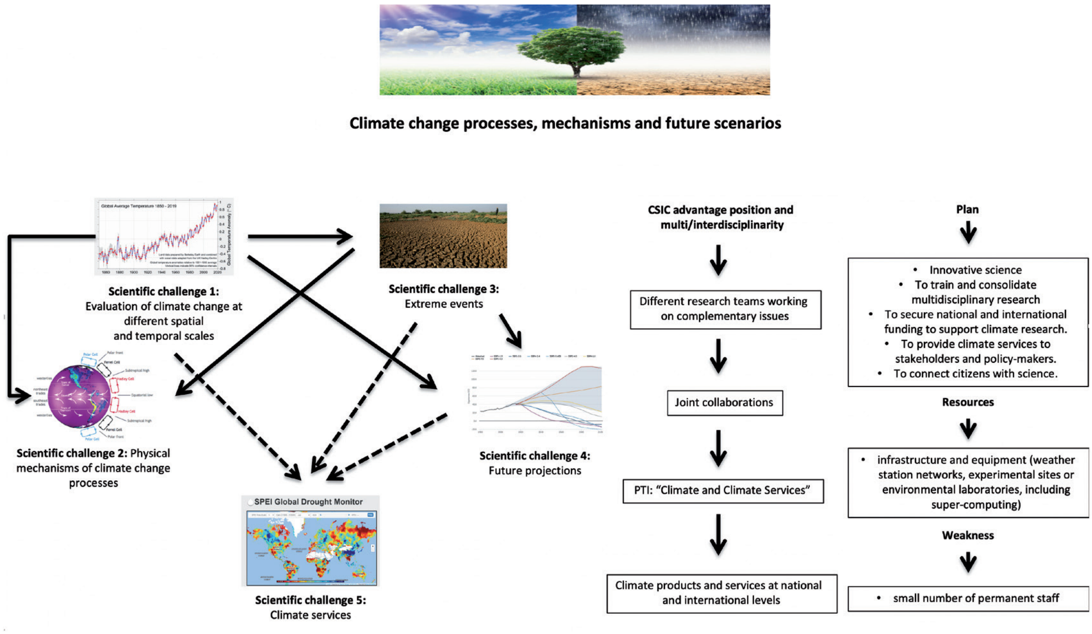
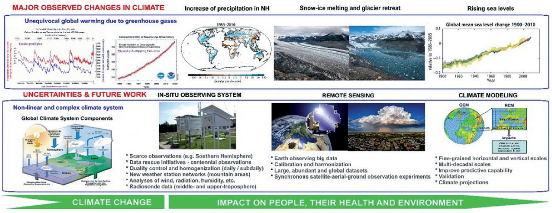
ACADEMIC SLIDE



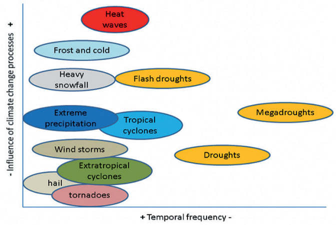
DISSEMINATION SLIDE

Climate change processes, mechanisms and future scenarios

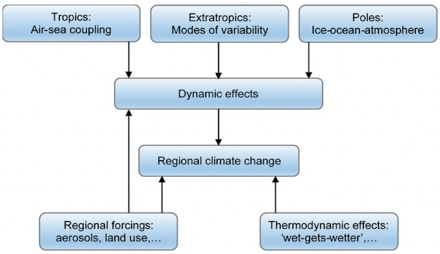
Scientific challenge 1: Evaluation of climate change



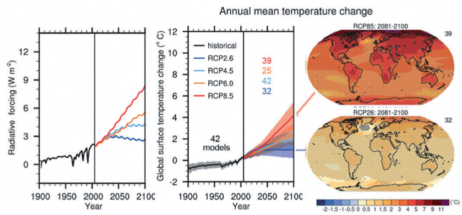
Scientific challenge 3: Extreme events



Scientific challenge 2: Physical mechanisms of climate change



Scientific challenge 4: Future projections



Scientific challenge 5:
Climate services

CHALLENGE 3

ABSTRACT

In the twenty-first century, biodiversity erosion has become a key scientific question at the time societal concern has increased. We propose theoretical, technological and policy-relevant challenges to preserve biodiversity and safeguard our options for future solutions to global environmental problems. We outline research areas to uncover naturally occurring processes, and to predict and mitigate the impact of global change.

KEYWORDS

ecosystem services | environmental policies | human-wildlife conflicts | invasive species | microbial communities | next-generation monitoring

CHALLENGE 3

PRESERVING BIODIVERSITY AND ITS FUNCTIONS UNDER GLOBAL CHANGE

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1. INTRODUCTION AND GENERAL DESCRIPTION

Biodiversity is threatened worldwide by human-induced rapid environmental changes in climate and land- / sea-use, pollution, and biotic exchange, i.e. by stressors ultimately linked to the rise of global human population and the advance of economic development (Chapin et al. 2000). The recent global assessment of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) warns that one million animal and plant species are threatened, alien species doubled in the last 50 years, and wild populations have lost about 1% of their genetic diversity per decade in the last 150 years. Moreover, 40 % of the world's land has been converted to agricultural or urban land and 87 % of the ocean has been to some extent altered. This means that biological diversity is eroded at all its levels, from the genetic variability of populations to the diversity of species and the ecosystems in which they live, a loss that ultimately compromises the functioning of ecosystems and their ability to provide services to humans (Loreau et al. 2001).

Although biodiversity should be protected for its own sake to maintain a healthy planet, and for the sake of humans for our own well-being, its preservation is often perceived as a trade-off with other competing interests such as human development or resource production. Delineating win–win approaches that balance conservation and human activities is difficult and complicate the optimization of conservation strategies. A single target similar to, e.g., climate-change objective of not reaching a global 1.5 °C increase in temperature above pre-industrial levels (Paris Agreement Report http://go.nature.com/2mmbWvt) cannot be realistically identified in the case of biodiversity with its multiple dimensions (Purvis 2020). As a consequence, the scientific community has to approach the biodiversity crisis from multiple perspectives, providing knowledge, tools and solutions that help optimising the outcome of different goals. This can be achieved by reducing knowledge gaps, synthesizing and conceptualizing the role of biodiversity in providing ecosystem services, and developing a unifying framework to study variation triggered by global change across biological scales. Theory construction should progress in parallel with technological advances for biodiversity monitoring and modelling, and, in close connection with disciplines external to natural sciences, serve to design policies aiming at preserving, managing and restoring habitats and species. This last step is crucial to reduce the mismatch between the scientific evidence of impacts on one side, and policies and societal expectations on the other.

One of the most important knowledge gaps is the quantitative assessment of human effects on ecosystem processes involving interactions among species in the complex natural and social networks where they occur, and their implications for ecosystem functions and the provision of goods and services. These interactions may involve species undergoing geographic range displacement or abundance shifts, and both native and invasive alien species. The status and function of microorganisms and the role of their diversity in ecosystems is another key issue that lack sufficient knowledge. Both species interaction networks and microbial communities represent hidden facets of biodiversity making invaluable contributions to ecosystem functions. On the other hand, the success of conservation planning and ecosystem-based management depends on our ability both to anticipate species' responses to global change and to manage conflicts arising from ecosystem conservation and economic exploitation (farming, fishing, hunting, use of exotic species, etc.). Understanding the social and political contexts underpinning these practices is necessary for sustainable wildlife management and the reformation of policies integrating environmental issues. Finally, sound empiric evidence builds both on manipulative experiments and on continuous monitoring and evaluation of ecological dynamics. A challenge in this context is the development of next generation technologies for the remote and non- invasive monitoring of species, ecological interactions and ecosystem properties. These include the application of new DNA technologies or remote sensors in satellites, apps, unmanned vehicles, to map variations in the state of biodiversity across time and space.

Here we propose nine challenges for (i) **filling knowledge gaps**, (ii) **advancing technology** and (iii) **seeking solutions for biodiversity conservation under global change**. Palaeontological approaches to the biodiversity crisis are presented in the Strategic Theme #14; we will prioritize here challenging points in which the ecological scale predominates —current and future scenarios— although evolutionary processes are also inherently involved when targeting biological responses to changing environmental conditions. The management of primary productivity is presented in the Strategic Theme #6. We focus here on the conservation of other important services provided by nature, including those provided by wild animals and microbial communities.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Current explanations and models anticipating responses to global change are often based on knowledge on biodiversity that is incomplete or directly missing for numerous taxa, geographical regions, ecological functions and interactions (Hortal et al. 2015).

Moreover, policies dealing with endangered species and ecosystem conservation often lag decades behind the publication of relevant science. Our key-challenges aim at reducing these gaps through theoretical, technological and policy-relevant advances. The functional properties of ecological systems are multifactorial and interactive. Even if solid theoretical models on how species coexist at the community level exist, they are often disconnected from empirical validations. The composition of ecological communities and the nature of species interactions are influenced by shifts in species geographical distribution and phenology caused by climate, by the spread of invasive species and other global change impacts. Predicting community dynamics under global change involves understanding the effects of different stressors and processes on local species' interactions, while to predict the responses of natural populations we need to know how fast adaptation can occur in novel conditions.

An important obstacle to develop more realistic models of current and future biodiversity distribution is that the data needed to build models are often scarce or absent. Collecting detailed information on millions of species around the world is an infeasible challenge for researchers, and field techniques may fall short of performing large scale and standardized monitoring. Low-cost and non-invasive remote sensors can be developed to monitor biodiversity over time and across different spatial scales as an alternative to human eye and ear. Moreover, high-throughput sequencing methods enable the simultaneous sequencing of thousands of genetic markers across whole genomes and can be used to assess the status of wild populations and species interactions.

Intrinsic positive relationships between biodiversity and the provision and stability of ecosystem services are accepted nowadays, not only among scientists, but also among environmental managers or policy makers. The dual goal of conserving biodiversity and nature's contributions to people is thus in the core of the environmental political agenda (e.g., the EU Biodiversity Strategy for 2030 https://ec.europa.eu/info/sites/info/files/communication-annex-eu-biodiversity-strategy- 2030_en.pdf, the 15th UN's Sustainable Development Goal https://sustainabledevelopment.un.org/). The Convention on Biological Diversity and other biodiversity-related multilateral agreements claim urgent changes in policy and human behaviour to preserve, together with biodiversity, our options for future solutions to global environmental problems (e.g., Aichi targets, www.cbd.int/sp/targets/). The integration of environmental issues into economic and social policies has entered the politic agenda (https://ec.europa.eu/environment/integration/integration.htm). These agreements, actions and policies are important because even when we have the knowledge to perform conservation actions, these need to be coordinated with economical and societal interests to be effective. The call for actions has permeated society deeply, and the COVID-19 pandemic has contributed to a raised awareness about the impact of wild animal consumption and habitat clearing on nature, and the indirect consequences for disease control. Keeping in mind the above demands, the goal of this chapter is to address the current specific challenges necessary to maintain or invert trends of biodiversity loss.

3. KEY CHALLENGING POINTS

3.1. Filling knowledge gaps

Tackling complexity in the relationship between biodiversity and ecosystem services

Global biodiversity loss is a central component of environmental crisis whose consequences largely overcome the simple decrease of species number. Much concern is about the decline of ecosystem functioning and services concomitant to the loss of species and their ecological interactions. Coping with biodiversity decays and properly managing ecosystem services, at the large spatial -but short temporal- scale required by humanity, still requires strong research efforts. Here, we urge, first, to disentangle the structural and functional complexity of the link between biodiversity and ecosystem services and, second, to assess the spatial scales at which complexity operates in real- world landscapes.

Ecosystem services rarely emerge from simple ecological functions provided by single species, but from the joint activity of large assemblages of species structured in complex networks of interactions. Even apparently well-defined services, like crop pollination, depend not only on wild pollinators but also on wild plants providing additional resources to these animals (Figure 1). Therefore, integrating the structure of interaction networks in the biodiversity-ecosystem functioning axioms is essential for re-interpreting the mechanisms that control the provision of multiple ecosystem services (Hines et al. 2015). In fact, different services may be represented as the functional outcomes of different sub-networks or modules, interconnected by common species with multiple roles (García et al. 2018). For example, plants interact with herbivores for biomass production but at the same time drive nutrient cycling with soil microorganisms. Topological measures of interaction complementarity may be thus used for analyzing the effects of biodiversity on simultaneous ecosystem services.

Multiple functions depending on interrelated biodiversity components lead to trade-offs, synergies and feedbacks among ecosystem services. A classical trade-off is that between agricultural production and agroecosystem services: intensifying agriculture for increasing crop yields leads to decays in natural pollination, pest-control and nutrient-cycling. Trade-offs also may emerge between ecosystem services and disservices, promoted by the same organisms through different functional roles. For example birds exerting pest regulation in crops may otherwise decrease production by damaging fruits. Synergies occur when

FIGURE 1—Ecosystem functions, such as pollination, often emerge from the joint activity of large assemblages of species. Picture by Paola Laiolo.

a given ecosystem service benefits from the increase in other, as for example when enhancing seed dispersal by animals drives vegetation expansion, which results in increased carbon sequestration. Feed-backs are a mechanism of synergism, through circularity in the reciprocal positive effects between interconnected ecosystem services. For example, pollination harnesses from the increased plant growth resulting from nutrient cycling which, in turn, responds positively to the accumulation of organic matter due to plant growth.

Discerning the spatio-temporal scales of the structural and functional relationships between different ecosystem services is also mandatory. Although complexity has been assessed through small-scale experimental and observational research, little is known about its relevance at the large spatial scales at which many services (e.g. water regulation, carbon sequestration) need to be managed. Paradoxically, these large scales are also those at which anthropogenic drivers erode biodiversity. Real-world landscapes must be thus interpreted as spatial mosaics for the interconnected exchange of species, interactions and ecological functions. Managing these mosaics for benefiting simultaneously biodiversity and people requires the integration of interrelated ecosystem services as well as the scaling-up of mechanisms determining the link between biodiversity and ecosystem functioning (Kremen & Merenlender 2018; Manning et al. 2019).

Unravelling the structure and ecosystem functions of microbial communities

In the early 1990s, the International Programme of Biodiversity Science DIVERSITAS, a programme promoted among others by the International Council of Scientific Unions (ICSU) and UNESCO, and now migrated to both Future Earth (http:// www.futureearth.org/) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), raised public awareness on the lack of knowledge on the diversity of the microbial world. This programme highlighted the crucial role that microbial biodiversity plays in the maintenance of many ecosystem resources and processes that benefit humans, and tried to reach public opinion and policy decisions. DIVERSITAS emphasized the immense genetic diversity of microorganisms and their crucial and unique roles as essential components of food webs and biogeochemical cycles and included "microbial biodiversity" within the nine fundamental cross-cutting research themes of critical importance for biodiversity science. On the whole, the sustained effort carried out for microbial ecologists in the last 30 years circumvented some of the methodological and conceptual concerns that had strongly limited the general perception of how crucial microbes are for Earth biodiversity and functioning, and initiated the effective transplantation of concepts and basic knowledge from the general ecology grounded on plants and animals to microbial ecology. The progress sequentially added on (i) cataloguing microbial biodiversity, and (ii) unveiling of spatio-temporal distributions and patterns. Some emerging facts and trends have already shown the large and multidisciplinary potential of microbial discoveries such as DNA polymerases to successful polymerase chain reaction (PCR), Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) and advanced genetic engineering, several biotechnological products present in our daily lives, and key microbial species as fundamental pieces to understand the evolution and generation of eukaryotes, among many others. Microscopic organisms have been, however, mostly excluded in conservation studies and microbiology has been developed as a scientific discipline lacking a natural history background. Microbes arise as an important part of the biological richness of any environments that should be considered as a fundamental component of the natural heritage and key components for ecosystems management and human well-being (Figure 2). Interdisciplinary Unified Microbiome Initiatives to understand and harness the capabilities of the set of Earth's microbial ecosystems are expected to raise in the coming years. Interestingly, currently we are only able to identify < 50% of the genetic material recovered from natural microbiomes missing what has been

FIGURE 2–Stratified lakes are appropriate environments for studying the links between composition and functionality in microbial communities. Pictures by Emilio O. Casamayor, Ricardo Guerrero and Xavier Triadó.

informally called the "biological dark matter", formed by genes that have an unknown function. Certainly this "dark matter" is the new and very exciting next frontier to be explored and unveiled, and this challenge needs of powerful computational approaches, large biological datasets and surveys, and improve the basic knowledge in physiology and cell biology. Additional challenges will also need to identify the presence or absence of key microbial species on which the whole microbiome network is articulated and those between which most of the energy and matter of the system circulates, as well as the degree and nature of the biological interactions between the different node components and between micro- and macroorganisms using systems biology approaches. Recent studies show microbial saprophytes and parasites to be more diverse and environmentally recurrent than previously expected, with highly specific interactions and a potential relevant role in food webs that needs still to be unveiled. Understanding the roles of the aboveground and belowground phytobiome and of the gut microbiome are major challenges to fully understand macroorganims traits such as growth, adaptation to abiotic stresses, immune activation, and behaviour, and on how to modulate these interactions for human benefits.

Understanding the ecological and evolutionary dynamics of communities under global change

The dynamics of ecological communities result from the interplay of ecological, evolutionary and biogeographical processes, as local coexistence of individuals and populations is the outcome of their adaptations to the biotic and abiotic environment, and the dispersal from other localities (Soberón 2007). It follows that local communities are, in a significant part, affected by processes occurring outside them. In practical terms, this implies that understanding community dynamics under global change involves understanding the effects of different stressors and processes on local species' interactions, metacommunity dynamics and species distribution ranges. These include:

(i)physiological constrains that determine the environmental conditions at which species can persist; (ii) dispersal and biogeographical processes that determine the localities reached by each species; (iii) resource availability that limits the establishment and growth of local populations; (iv) stochastic fluctuations in species populations due to metapopulation dynamics; and (v) the effect of biotic interactions on species' responses to the environment (Hortal et al. 2010). Under this framework, species traits would (co)evolve along large spatial extents (Thompson 2005), forming a regional pool of species that are then filtered by local conditions determining species coexistence.

The study of species selection is central to understand community assembly and evolution across scales (Vellend 2016). When subject to global change stressors, species will be selected through assembly processes and/or evolve novel adaptations locally to adapt to the new conditions in the community. The greater the stress, the stronger will be the selection of individuals with particular combinations of trait values that allow them to thrive around the new environmental optima (Mason et al. 2013). Two main kinds of selection processes operate under species coexistence (HilleRisLambers et al. 2012). Equalizing processes select individuals and species with similar niches, minimizing their fitness differences along gradients; this happens, for example, when biotic and/or abiotic conditions impose a stress that selects individuals with similar niches (environmental filtering) (Figure 3), or when facilitation

FIGURE 3—Abiotic conditions impose a stress on alpine organisms and select individuals with specific ecological niches (environmental filtering). Picture by Leandro Meléndez.

processes select species with particular traits. Stabilizing processes select for dissimilar niches, maximizing the fitness differences along these gradients; this typically happens in limiting similarity processes, where competition for a finite resource selects coexisting individuals with differing niches and/or phenotypes (Mason et al. 2013). Here, variations in traits of functional importance can help understand the mechanisms behind species selection, and scaling the effect of abiotic gradients and biotic interactions up to the community level (Pausas & Verdú 2010). Stabilizing and equalizing processes would produce different communities, as strong abiotic filters slow down the pace of competition allowing for the co-existence of functionally similar species, while strong biotic competitive interactions select species that avoid trait overlap to escape competition.

However, both types of effects may create similar patterns, as they can select for the same or correlated traits and/or phylogenetically closer species, and superior competitors can also have a disproportionately large effect on other species (HilleRisLambers et al. 2012). There is a significant amount of sound and well-developed ecological and evolutionary theory about all these aspects of selection separately (e.g., Thompson 2005, Vellend 2016). However, their effects are complex and intrinsically scale- dependent, and there is a dearth of information about how they interact and shift in importance as environmental conditions change at different scales. Without such basic information, forecasts of community dynamics under changing conditions will always present a large degree of uncertainty. Part of this uncertainty comes from the lack

FIGURE 4–Integrating observational evidence with experimental evidence of phenotypic trait variation in response to shifts in abiotic and biotic conditions is fundamental to understand species responses to global change. Picture by Paola Laiolo.

of integrative studies that consider several scales and processes simultaneously. Given the complexity of ecological systems researchers have frequently resorted to dividing the system into smaller and more tractable units, thus analysing a set of drivers at a fixed scale. As a consequence, different disciplines have specialised in certain scales developing entire bodies of knowledge based on divergent –and sometimes contradictory– core ideas. Solving this Gordian knot requires combining observational and experimental approaches to help connecting the theoretical bodies of biogeography, macroecology, ecology and evolutionary biology into tractable models that combine metacommunity dynamics of species selection with the evolution of traits and niche under coexistence (Figure 4).

With this challenge, knowledge will advance in three major fronts. First, the integration of different bodies of ecological and evolutionary theory will allow incorporating the complex effects of environment and coexistence into the new evolutionary synthesis. Second, we will get a better understanding of how species and communities adapt to different aspects of global change, with the associated changes in ecosystem functioning. Finally, enhanced adaptive management of biodiversity through improved metacommunity and species distribution models will increase the reliability of forecasts of biodiversity dynamics under different global change scenarios.

3.2. Advancing technology

Next-generation monitoring: technologies and analytical methods to detect and study the impact of global change on biodiversity

Addressing the formidable impacts of global change on biodiversity requires massively increasing our capacity to monitor different aspects of biodiversity over large spatiotemporal scales. A key challenge is to develop a new generation of affordable monitoring technologies that can boost the amount and quality of data gathered on species, communities, habitats and threats (Pimm et al. 2015). Despite the long tradition of using monitoring technology in ecology and conservation (including some well- established areas like radiotracking, biologging, remote sensing, camera traps), recent advances have brought a staggering range of more experimental applications of technology (from tiny radio-trackers on insects, to continental-scale monitoring of bird migration using weather radar stations) that are not yet widespread.

Research is critical in two linked fronts to address this key challenge of producing next-generation technologies for biodiversity monitoring. First, more work is needed in mainstreaming the use of novel and emerging technologies that are currently experimental or even conceptual. Such technological maturity is achieved by extensive field trials, studies of cost-efficiency compared to traditional monitoring methods, and developing associated analytical and computational methods to deal with the idiosyncrasies of new data types (e.g. false positives) and handle increasingly larger data volumes (e.g. Artificial intelligence-based species identification from pictures and sound files). Technologies with great potential for large-scale monitoring that are undergoing rapid development include next-generation sequencing of genetic material (NGS, see the next challenging point) and acoustic monitoring, particularly surveillance monitoring of environmental change using soundscape-level metrics as early-detection systems. A third opportunity is using technology to unleash the full potential of citizen science (Figure 5).

The second research front is about understanding how to massively scale up the global availability and effective use of monitoring technology. A growing movement is calling for the conservation community to become

FIGURE 5—Acoustic monitoring devices, citizen science programs and unmanned aerial vehicles can help surveying and mapping biodiversity. Pictures by Federica Rossetto and Begoña García.

innovators (Berger-Tal & Lahoz- Monfort 2018) and actively seek to create technologies that are (i) affordable, (ii) field- ready and (iii) offer specific functionalities. Success requires investigating the international leadership, institutions, processes and funding mechanisms that need to be established for the development, production and distribution of targeted monitoring technologies to be scalable and viable over the long term (Lahoz-Monfort et al. 2019). Open-source technology is likely to be instrumental in this process, but to date only a handful of open-source devices for biodiversity monitoring are achieving large-scale uptake (e.g. *AudioMoth* for acoustics, Figure 5). This is uncharted territory and a thorough exploration of some key areas (e.g. business models that support development of affordable "technology for good", public elicitation of technology roadmaps that reflect real monitoring needs, multi-NGO vs. intergovernmental institutional leadership) is essential for collaborative open-source innovation to become a viable reality with global impact.

Next generation monitoring will play a key role in shaping the emerging efforts on modelling in the current biodiversity panorama. Assessing the potential impacts of global changes on biodiversity requires the development of modelling and the use of these models under various scenario assessment frameworks allowing the comparison of likely biodiversity impacts under different future societal trajectories. The current challenge is in developing and evaluating models that correctly capture spatial and temporal dynamics in biodiversity. However, these data are generally scarce to adequately capture these patterns. Integration of large-scale, ambitious, cost-effective monitoring with current modelling efforts developed at different spatial scales emerges as a key target of future integrative efforts in biodiversity research.

Next-generation monitoring of genetic diversity

It has long been recognized by the scientific community that genetic diversity is of fundamental importance for the survival of populations even on a conservation time scale (Allendorf et al. 2010), but genetic diversity has only recently been incorporated into conservation goals and laws, such as the Aichi Biodiversity Targets. In order to monitor genetic diversity in populations of wildlife, it is necessary (i) to broadly sample the populations, and (ii) to measure variability at genetic markers that are sufficiently variable to accurately measure genetic diversity in a way that can be compared against other samplings of the same population (Figure 6).

FIGURE 6—Genetic diversity has been incorporated into conservation goals and laws, thus it becomes important to measure it in ways that are useful for determining if conservation targets are being met. UMIB Molecular Ecology Lab. Picture by Paola Laiolo.

Methods have been developed to sample environmental DNA (eDNA) from soil or water to determine the presence or absence of species (both terrestrial and aquatic; Sales et al. 2020). These studies generally yield a confirmation of presence of a species or genus, based on fragments of single genetic markers, although this is far from sufficient for other scopes, for instance to monitor genetic diversity through time in a population (Forcina & Leonard 2020). NGS technology can help expanding these and other non-invasive sampling methods (e.g., collection of feces, hair or saliva) to anonymously sample the local population of one or more species simultaneously.

Several different genetic markers have been used to measure genetic diversity in populations, and changes in genetic diversity in populations through time. Apart from eukaryote mitochondrial or chloroplast DNA sequences, the most common markers are single nucleotide polymorphisms (SNPs) and microsatellite size polymorphisms. SNPs are distributed throughout the genome, and very many of them can be genotyped, but finding them requires a lot of system specific work which is not easily applicable to other species, or even other populations of the same species. Microsatellites are highly variable, and numerous throughout the genome. Systems set up in one species are often useful also in other related species. The normal scoring of these loci, however, is very fickle and so results cannot be compared between labs or even projects within a lab.

Introns may be a good in-between marker. There are very many of them distributed throughout the genome, there is a reasonable expectation for variability without prior data, and the primers to amplify them are somewhat conserved and so can be used across many related taxa (Forcina & Leonard 2020). They have not been extensively applied at the population level, likely due to logistics. Until recent advances NGS, it was both very time consuming and expensive to sequence a panel of these markers in many individuals. Now large multiplexes of introns can be amplified in single reactions and sequenced in large pools (i.e. Camacho-Sanchez et al. 2018). The data generated in this kind of project have the important benefit of being easily comparable between projects and labs- a key character of a useful tool for monitoring. Microsatellite loci, discarded above as a good tool for monitoring because of the lack of comparability of genotypes across projects, may also be rescued by NGS. If these highly variable loci could be successfully sequenced instead of the standard size polymorphism, they may be become useful in the context of monitoring. Intron and microsatellite sequencing are less developed, and very much less data is available for comparison, but these are issues that can reasonably be rectified, and monitoring the genetic diversity of populations will in any case require the collection of population specific data on an on-going basis.

NGS methods have strongly advanced our knowledge of microbial communities, although we are still far for a complete catalogue of microbes and its distribution and dynamics on Earth, and this limitation will guide future research in the coming decades. NGS can accelerate the discovery and characterization of microbial diversity, permit establishing reliable databases, collecting and exchanging information on the biological characteristics of microorganisms, and capturing microbial functional diversity. A wide array of powerful techniques has been developed to deal with in situ status of microbial diversity (Casamayor et al. 2002). These include, i) metagenomics - the study of large DNA fragments obtained directly from the environment and the use of high-throughput DNA sequencing and further reconstruction of large pieces of genomes using bioinformatics, ii) comparative genomics - using metagenomes and available genomes in databases to both make inferences about ecology, biology and evolution, and to search for relevant functional genes, iii) functional genes surveys by metatrancriptomics and quantitative PCR, iv) well-analyzed large gene datasets, high statistics performance, and high computational power.

3.3. Protecting biodiversity

Mitigating the impact of invasive species

Biological invasions are considered one of the five most important drivers of biodiversity loss: they affect native species richness and abundance, increase the risk of native species extinction, affect the genetic composition of native populations, change native animal behaviour, alter phylogenetic diversity across communities, modify trophic networks and alter ecosystem productivity, nutrient cycling, hydrology, and disturbance regimes (see refs in Pyšek et al. 2020). Both the numbers and distributions of invasive species are increasing in many parts of the world, to the extent that the biogeographic distinctiveness of different regions is becoming blurred. Furthermore, invasive species are directly or indirectly related to 54% of reported animal extinctions (Clavero & García-Berthou 2005) and are currently listed as a major threat for 27% of Red List species.

To unravel the contribution of invasive species to the biodiversity crisis and mitigate their impacts, we need to advance in three major fronts. First, we need to improve basic knowledge. Past research on biological invasions has mainly focused on the ecological factors determining success and distribution, focusing on particular species, habitats or ecosystem functions, and on short-term consequences. In contrast, the interaction of invasive species in complex networks, and their impacts on ecosystem services and human health have received little attention. Moreover, current knowledge is strongly biased towards terrestrial habitats and services that have marketable values (agriculture yields, forestry production, human health), whereas aquatic habitats and nonmarketable services are largely ignored (Gallardo et al. 2019). Furthermore, long- term consequences of past and current invasions remain largely unknown. These gaps in knowledge remain pervasive challenges that hinder the effective prevention and management of invasive species. In the future, it will become increasingly important to integrate evidence across habitats (terrestrial, freshwater, marine), scales (local to continental) and impact outcomes (on biodiversity, ecosystem services and human well- being).

Second, we need developing future scenarios of invasion. In contrast to other drivers of global biodiversity loss, such as climate or land use change, we still lack a thorough understanding of the potential numbers and impacts of invasive species on biodiversity and human livelihoods for the decades to come. Future scenarios would set up a baseline against which to compare the effectiveness of management interventions, to anticipate the number of invaders and their associated impacts under a range of future climate or socio-economic scenarios, and to compare the ecological and economic costs of "best" against "worst" case scenarios. This challenge will require additional data to update and complement global databases of biological invasions, particularly for underrepresented taxonomic groups, such as microorganisms. It will also require an understanding of the synergies between biological invasions and other drivers of change such as transport, climate, land-use and socio-economic developments, and their context-dependencies. Such scenarios are fundamental not only to direct future research but also to support policy and management.

Finally, we need screening methods. Part of these methods are described above, here we outline those specifics for invasive species. The arrival of these species is extremely difficult to detect, and once established, they are very challenging, often impossible, to eradicate. New technologies are emerging that can support early detection, including environmental DNA, drones, robots, light-based technologies, acoustic detection, e-nose devices, nanobiosensors, artificial intelligence, smartphones that facilitate citizen science, syndromic surveillance of social media, big data analysis to detect patterns, remote sensing and satellite imagery (see Martínez et al. 2020 for a review). Novel technologies also offer invaluable opportunities to mitigate the impacts of invasive species, through for instance, biological control, robot manipulation, synthetic gene drives, virtual fencing, anti-fouling coatings, new and more sustainable toxicants that would allow an early response to upcoming threats. The challenge is not only to develop these technologies, some of which are already being used successfully (e.g. Wangensteen et al. 2018), but rather to scale up their widespread deployment and implementation, ideally integrated into a national biosecurity monitoring network.

The three research fronts outlined above are highly inter-related and constitute a bottom up approach from the laboratory or field site to the market, directed to improve the prevention and management of biological invasions, thereby protecting biodiversity and ecosystem services.

Halting the loss of pollinators

The so often called "pollinator crisis" provides a textbook example of a conservation issue with far reaching implications for ecosystems, the economy and our society. As such, it is illustrative of how different sectors can work together to solve a common problem. Pollinators were a largely ignored component of biodiversity until early 2000's, with most conservation actions devoted to large mammals, birds and other iconic species. A parallel recognition of their role in ecosystem functioning (i.e. mediating the reproduction of > 80% of plants) and ecosystem service provision (i.e. maximizing production of 75% of crops) along with initial observations of pollinator population declines triggered a scientific and societal alarm. As a result, the conservation of pollinators has acted as an umbrella to conserve other neglected but important invertebrates and has achieved key conservation milestones, including changes in policy regulations in agricultural habitats. However, despite recent advances, we are still far from understanding or reverting pollinator population declines.

Pollinators are a diverse group of animals, potentially responsible for reproduction of more than 80% of plant species worldwide (Ollerton et al. 2011). Bees are generally considered the most important pollinators, especially for crops (Klein et al. 2007).

However, many other animals provide pollination services, including other groups of insects like Coleoptera, Lepidoptera, Diptera and non-bee Hymenoptera. In addition, birds, bats, rodents and even lizards are pollinators of many plants, especially at lower latitudes (Winfree et al. 2011). However, despite increasing concern about the decline of pollinators worldwide, data on population trends are scarce and often geographically and taxonomically biased (Bartomeus et al. 2018). For example, a recent IUCN report concluded that even for Europe's comparatively well-studied bee fauna, more than 55% of bee species fell into the 'data deficient' category. Hence, we first need to monitor populations to assess the current status of species. As in many other taxa, researchers have now developed strong consensus that disturbances such as habitat destruction, land-use intensification, chemical exposure, exotic species and climate change are causing pollinator declines and often act synergistically (Goulson et al. 2015). We need to integrate this knowledge into conservation actions that actually work for pollinators. This is more easily said than done, as theoretical models are often disconnected from empirical studies, and our predictive ability on how entire communities will respond to conservation actions is poor.

Finally, pollinator conservationists have advanced a lot in societal awareness, facilitating the development of pollinator friendly policies. However, current research shows that without integrating economic sectors (e.g. farmers), the wider society (e.g. NGOs), policy makers and conservationists into the conversation, efforts to change how we manage the landscape for pollinators are unsuccessful and that despite regulations, our farming systems are still unfriendly to wildlife. We still need to walk a long road to create multi- and trans-disciplinary teams that transform conservation actions into win- win situations. Ecological researchers cannot do this alone and need to team up with social scientists and involve all relevant stakeholders. Reversing the pollinator crisis will not only be a great conservation success, with direct implications for human well- being, but will teach us a lot about how to leverage ecological information, public engagement and economical decisions to achieve meaningful conservation actions in other taxa.

Linking ecological and social research for managing wild vertebrates for healthy ecosystems

Wild vertebrates are an integral part of biodiversity, and are involved in many of the services provided by the ecosystem not described in other points. For example, they play key roles in nutrient cycling (i.e. supporting services), actively participate in disease regulation (i.e. regulating services), provide food and materials used by people (i.e. provisioning services) and are important for recreation, tourism, and cultural uses and for aesthetic reasons (i.e. cultural services) (e.g. Whelan et al. 2008) (Figure 7). The conservation of wild vertebrates is threatened by many components of global change due to habitat loss, over-exploitation by humans, invasive species, pollution and climate change (IPBES 2019). Wildlife loss has consequences for ecological processes that support biodiversity and may have also serious socioeconomic impacts. The maintenance of wild populations of vertebrates in humanized landscapes such as Western Europe sometimes needs active management of their populations or their habitats (this is clearly the case when considering endangered species). However, management aimed at increasing their numbers can come into conflict with other human activities like farming or hunting (Redpath et al. 2013). On the other hand, populations of some wild vertebrates have increased substantially in recent decades (as a consequence of human-induced changes in the environment, or directly from management actions), and impact human livelihoods or even other species or natural processes in the ecosystem (e.g., invasive alien species of birds and mammals, increasing populations of certain ungulates, particularly wild boar, etc.). In these cases, management to maintain populations under certain levels is sometimes seen as one of the options to reduce these impacts (Martínez-Jauregui et al. 2020).

FIGURE 7—Wild vertebrates are an integral part of biodiversity involved in many ecosystem services. Picture by Alberto Fernández Gil.

However, the increase in society of certain values such as animal welfare or even attributing to wildlife the same rights as humans implies that parts of the society may strongly oppose this management, despite the ecological damage arising from not doing it (Martínez- Jauregui et al. 2020), which may render ecologically-efficient solutions a source of social conflicts. Conflicts over wildlife management are increasing and are often costly to both humans and involved wildlife species (Redpath et al. 2013), and therefore their effective mitigation through scientific solutions should be a priority.

Sustainable wildlife management, understood as the management of wildlife species to sustain their populations and habitat over time with consideration to the socioeconomic context in which it is implemented (Cardador et al. 2015), requires a good understanding of both the biological/ecological as well as the socioeconomic systems, and this can be only achieved through a multidisciplinary approach that integrates the natural and social sciences (White et al. 2009). A key scientific challenge is to find situations that are both ecologically efficient and socially acceptable.

Increasing our understanding on human-wildlife relationships and how these have evolved is critical, particularly in this period of global change in which most people live in urban areas. A major challenge is assessing the positions and preferences of the society towards different alternatives of wildlife management in terms of efficiency, cost and human-ness, particularly in the face of uncertainty in relation to the ecological efficiency of different alternatives. Reducing that uncertainty (through better understanding of the relationships between species in the community and their environment, and response to human-induced changes in that environment) is another crucial challenge.

Nature conservation through laws and policies

Conservation laws and policies, adopted by human institutions at (sub)national or international levels, are aimed at forbidding or regulating human activities that negatively impact ecosystems, habitats and species, in order to slow or stop the degradation of nature. Some of them aim for the recovery of nature such as, for example, the US Endangered Species Act, the EU Habitats Directive, or the Convention on Biological Diversity. Conservation laws and policies are increasingly recognized as important elements of the available toolkit for an effective preservation of nature.

However, the political decision of adopting a given conservation legislation alone is not a guarantee of success in conservation, and the current practices in the implementation of these instruments do not appear to be able to avert the current biodiversity crisis significantly. For example, the recently released 2020 evaluation of the IUCN Red List shows that 22% of the mammal species evaluated (5,899) are threatened. The world's nations previously failed to meet targets agreed in 2002 to achieve a significant reduction in the rate of biodiversity loss by 2010, and are unlikely to meet in 2020 the Aichi targets agreed under the Convention on Biological Diversity. It is also uncertain how current debates on possible targets for the future will avoid the same observed failures.

This situation raises the question of whether, apart from some particular cases, existing conservation instruments are fit for the purpose of preserving populations, ecosystems, and nature, and if and how their effectiveness could be improved. Although theoretically conservation laws and policies seem effective tools for conservation, and integrating environmental concerns into sectorial policies is a priority for sustainable development for many nations, several pitfalls still jeopardize the power of these instruments, such as poor coordination at national and subnational levels, failures in the integration of the best available knowledge, interpretive uncertainty, implementation, compliance, transposition or enforcement failures, or the weakening of these instruments (López-Bao & Margalida 2018). Imperfect legislation can result in distrust and decreasing compliance, and even leading to conservation conflicts. The increasing interest among conservation professionals in boosting the effectiveness of conservation laws and policies requires addressing these limitations, strengthening the interface between conservation science and policy-making. If human societies aim to find a balance with nature preservation, we need to understand, implement and enforce conservation laws and policies properly. Why does conservation succeed in some countries but fail in others? Answering this question will require effective inter- disciplinary approaches, promoting the intersection among ecology, law, policy, and social sciences (which aim to understand compliance and societal norms beyond policy). There is a challenge in understanding the range of measures used by different nations to ensure the effective implementation of conservation laws and policies. This endeavour would benefit from global assessments of the state of the effective implementation of these instruments.

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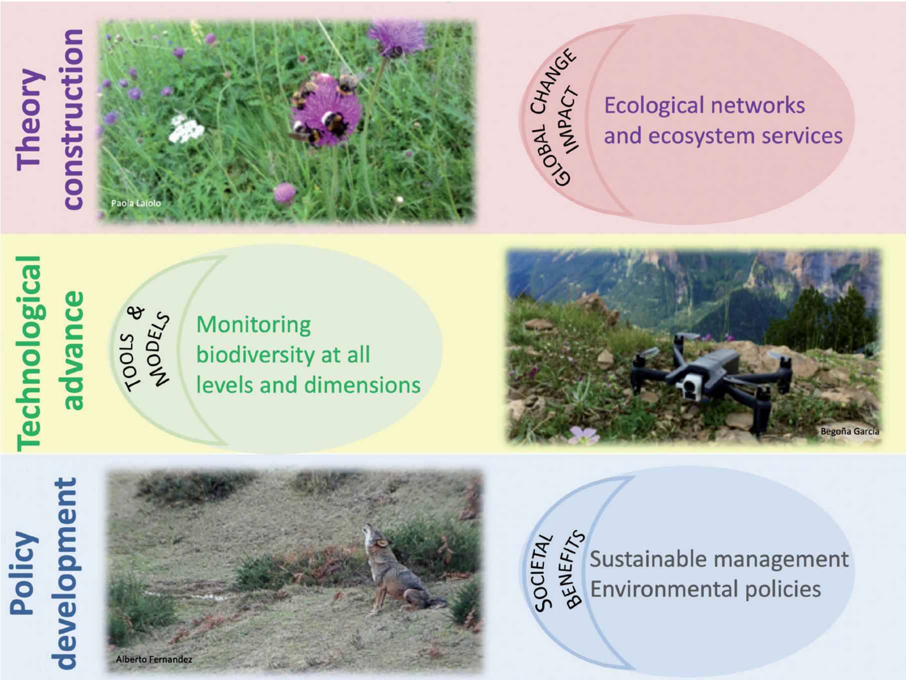
ACADEMIC SLIDE



DISSEMINATION SLIDE

CHALLENGE 4

ABSTRACT

The Polar Regions are key Earth's climate regulators and, hence, any perturbation in their baseline conditions can have global repercussions. Owing their intrinsic particularities such as the presence of huge amounts of sea and continental ice, their terrestrial and marine ecosystems are highly sensitive to temperature fluctuations. In fact, both the Arctic and the Antarctic Peninsula are the regions where temperature has raised most and faster than any other Earth's place. Moreover, other environmental issues related to anthropogenic changes such as the occurrence of contaminants, invasive species, emerging diseases and exploitation of living marine resources are also affecting the Polar Regions. Therefore, sound, detailed and long-term knowledge of the polar systems functioning, interactions and feedbacks is of paramount importance to establish and characterize the main impacts and consequences in both polar and extra-polar latitudes. Only then, efficient and environmentally friendly measures would be established both to mitigate the negative effects of current anthropogenic impacts and to protect polar ecosystems.

KEYWORDS

Arctic | Greenland | Antarctica | polar terrestrial and marine ecosystems | polar oceans | polar amplification | long-range pollutant transport | polar biogeochemical cycles | cryosphere

CHALLENGE 4

GLOBAL CHANGE AT THE POLAR REGIONS

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1. INTRODUCTION AND GENERAL DESCRIPTION

There is growing scientific and political awareness of the importance of Polar Regions (PR) as an integral part of the Earth's climate system, and of the need to ensure their integrity in the context of climate change. Climate change is rapidly altering the global environment, with some of its consequences being more prominent in the PR (Figure 1). The increase of CO_2 concentration levels due to human activities has clearly affected the PR since at least the 1980s, increasing the temperature and consequently inducing ice melting. The effects are revealed as ice retreat at polar glaciers in the Arctic Ocean (Stroeve and Notz, 2018) and in areas of the Antarctic Peninsula (IMBIE Team, 2018). Indeed, 2019 was the second hottest year in the historical (140-yr long) record and a significant reduction of the sea ice extent was recorded in both poles (NOAA, 2020). Such a threat poses a severe risk for the entire planet but also makes the PR exceptional sentinels to monitor and better understand and face global change challenges.

The PR have unique geographical and climatological characteristics, with low temperatures and lack of light during the winter, as well as relatively wide temperature oscillations between day and night during summer. They include the geographical areas most affected by the recent increase of temperatures due to anthropogenic activities (Figure 1). While this warming is clearly affecting the entire North Pole (also known as the Arctic Amplification (AA) phenomenon), temperature changes display a much more complicated spatial and temporal pattern on the Antarctic continent, including an overall warming from the 1950s to early 2010s followed by a significant cooling, as well as larger warming trends in West Antarctica than in East Antarctica. The overall changes in both PR have been attributed to human activities (i.e., increasing concentrations of greenhouse gases, with an additional role of stratospheric ozone depletion in the Antarctica. However, the precise mechanisms proposed to explain the AA (sea-ice loss, reduced outgoing longwave (LW) radiation due to a stable polar temperature profile, increased downward LW heating due to increased water vapor and clouds, and increased poleward energy transport, among others) or the asymmetric E-W Antarctic warming (e.g., positive trends in the Southern Annular Mode in austral summer and autumn), and their relative importance still remain poorly understood and require large research efforts.

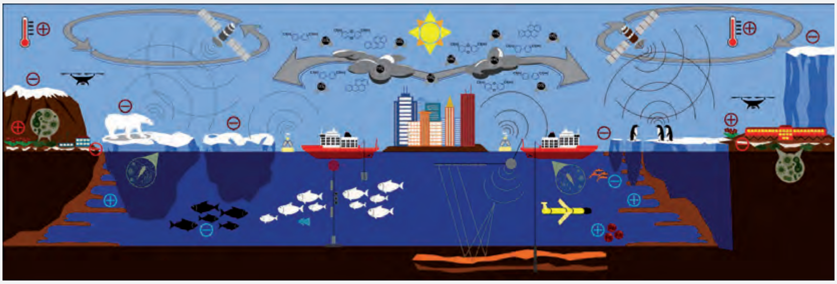
On the other hand, the Polar Oceans are undergoing a profound transformation (see also Thematic 13). The rapid decline in Arctic sea ice extent (SIE) and volume, clearly illustrates the sensitivity of PR to global warming (Figure 1). The ratio of decrease in September sea ice minima is estimated in 12.8 ± 2.3 % per decade (IPCC, 2019). The proportion of Arctic sea ice at least 5 years old declined from 30 % to 2 % between 1979 and 2018 and over the same period, first-year sea ice proportionally increased from approximately 40 % to 60–70 % (Stroeve and Notz, 2018). June snow cover extent on land in the Arctic declined by 13.4 ± 5.4 % per decade from 1967 to 2018, for a total loss of approximately 2.5 million km^2, predominantly due to the increase of surface air temperature (IPCC, 2019). The annual trends of SIE in Antarctica and its five sectors (Weddell, Ross, Bellingshausen and Amundsen Seas, and Indian and Pacific Oceans) are statistically significant, and the SIE trend of the Antarctic Peninsula cannot be explained by natural climate variability and might be linked to the recent anthropogenic temperature rise (Ludescher et al., 2019).

To date, global mean sea level (GMSL) has increased by ~22 cm since 1880, being among the clearest global responses to anthropogenic global warming. The IPCC Fifth Assessment Report (AR5, 2013) and the Special Report on the Ocean and Cryosphere in a Changing Climate (2019) identified the future evolution of polar ice sheets as one of the most dramatic unknowns in global climate projections, hampering reliable estimations of future GMSL rise. The AR5 estimates were limited by a lack of scientific knowledge of Antarctic ice sheet dynamics, which was identified as a tipping element: "*based on current understanding, only the collapse of marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the 21st century*." Quantifying the future and pace of GMSL rise and our long-term commitment to higher seas is essential. For this reason, it is critical to assess the credibility of future climate and GMSL projections, as well as past climate sensitivity estimates. Reconstructing past global climates and their impact on our planet to guide future projections is, however, a challenging task. It requires the recovery of strategically located geophysical and sedimentary sections containing the most continuous and high-resolution (decades to thousands of years) records of processes, rates, mechanisms and impacts of past natural climate variability, including abrupt climate changes and climate tipping points.

At the current pace of CO_2 emissions, global mean temperatures would reach 1.5 °C above pre- industrial levels by the 2040s (2030-2052, [5-95] % confidence level; IPCC, 2019). Earth's paleoclimate records reveal that warming between 1 ºC and 2 ºC (within the Paris Agreement range) and higher (>2 ºC) has resulted in very different states of Greenland and Antarctica ice sheets and wide ranges of GMSL change. Sediment records show the risk of ice sheet melting increases substantially even at 1.5 °C, causing 6-9 meters GMSL rise. Paleoclimate archives in marine sediments show that above 2 °C sustained global warming enhances melting and calving, and catastrophic collapse of ice shelves can occur, before removing marine ice sheets grounded in deep sub-glacial basins.

Long-range atmospheric and oceanic transport of organic pollutants, including legacy Persistent Organic Pollutants (POPs) and contaminants of emerging concern, and their bioaccumulation in polar food webs, represent major threats for both natural ecosystems and humans (Figure 1). Climate change affects both transport and fate of organic contaminants in the abiotic environment, ecological and ecosystem changes, and uptake and accumulation in the food webs. Therefore, it can reshape contaminant exposures in wildlife and humans through both physico-chemical processes and ecosystem-related changes. For instance, the rates of degradation of environmental contaminants can change under changing environmental conditions; melting of ice and snow, as well as thawing of permafrost and warmer temperatures may enhance the release of chemicals that have accumulated in soils, glaciers and surface ocean waters. In the context of combined climatic and

FIGURE 1—Main threats currently affecting the Polar Regions (PR), and some of the main techniques employed to characterize these threats. Minus signs indicate decline (i.e., wild life and sea-ice) whereas plus signs mark increase (i.e., temperature and invasive alien species). Horizontal arrows indicate transport towards PR. See the text for further details.



biogeochemical factors, global change involving different temperatures and organic matter stocks in the sea and land will affect the re-volatilisation and reservoirs of organic contaminants (Cabrerizo et al. 2013). Today, the field of POPs research faces the challenge of quantifying and forecasting the impact of POP contamination in the PR in the absence of a robust understanding of past and present contaminant input, environmental behaviour and biological effects, especially in Antarctica. Developing such robust understanding as well as the main adverse effects on the polar ecosystems is therefore essential. Furthermore, recent studies have witnessed that the levels of some legacy POPs have decreased in the Arctic, reflecting their ban in the last decades under the Stockholm Convention or previous national or international regulations, but are being remobilizing due to climate change. However, the steadily increasing list of new chemicals of concern poses further financial and technical challenges to comprehensively assessing the pollutant occurrence at monitoring stations and their impacts. Impact of organic pollutants can be triggered by the joint effect of complex mixtures rather than individual chemicals, with mechanisms that have received little attention (Cerro-Gálvez et al. 2019). It is of paramount importance to solve these challenges in order to understand the chemical behaviour and interactions of legacy and emerging pollutants.

Trace metals (TMs) occur naturally in the ocean, mostly as colloids or absorbed onto organic and inorganic suspended particles, and tend to accumulate in living organisms and bottom sediments. Some TMs, such as cadmium

(Cd), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn) or zinc (Zn), among others, are critical for marine life and therefore influence the functioning of ocean ecosystems and the global carbon cycle (Figure 1). For example, they play a key function in carbon fixation (Fe and Mn), CO_2 acquisition (Zn, Cd, Co), silica uptake by diatoms (Zn, Cd), calcifiers (Co and Zn), nitrogen fixation and synthesis of photopigments (Fe), nitrification, denitrification and organic nitrogen utilization (Cu and Fe), methane oxidation (Cu), etc. On the other hand, these elements may be present in excess due to human activities and, along with other metals [e.g., arsenic (As); mercury (Hg); lead (Pb)], can negatively affect ecosystem health (Morel and Price, 2003). Despite the recognized importance of these trace elements in the ocean, our ability to exploit the knowledge of their attributes is limited by uncertainties in their sources, sinks, internal cycling and chemical speciation.

Terrestrial ecosystems of PR are hard for life; they are ice covered during a large part of the year and marine ecosystems are affected by seasonal changes in sea ice. However, both harbor microbial communities specially adapted to these conditions and vulnerable to environmental changes (Figure 1). In addition, in the Polar Oceans there are important physico-chemical changes during the warm season, such as a decrease in salinity, an increase in inorganic and organic nutrients and the absorption of CO_2 due to seasonal sea ice melting (Anderson and Jones, 1991). This results in blooms of different groups of phytoplankton and the consequent increases in the abundance, activity and diversity of their immediate predators (zooplankton), as well as of microorganisms (prokaryotes, protists and viruses). In both polar regions, the capacity of marine ecosystems to withstand the cumulative impact of a number of pressures, including climate change, pollution and overexploitation, acting synergistically is of greatest concern and must be investigated.

Polar wildlife is characterized by showing adaptations on physiology, morphology and behaviour that allow species to survive in extremely cold environments. Such adaptations however, make polar species highly vulnerable to environmental changes considering the narrow range of tolerance they can bear (Figure 1). While temperate species can move toward the poles tracking the presence of more suitable environments to scape warming, polar species cannot find new places as they live in the end of the planet, and their probability of extinction increases. Despite the different human fingerprints in the Arctic and Antarctica, there are evidences of changes in the ecosystems of both

PR in the most remote regions. Climate change or contamination, invasive species, emerging diseases, fisheries exploitation are some of the factors contributing to the global change whose effects affect directly or indirectly the animal species inhabiting PR as some of the most iconic species like polar bears (Molnar et al. 2020) or penguins (Barbosa et al. 2012). The identification of the effects of global change on polar species and the underlying mechanisms are fundamental to understand the magnitude of effects and to evaluate their resilience to establish mitigation strategies that alleviate the effects and eventually reverse their consequences. This only can be achieved by developing a set of biological indicators (i.e., population size, breeding success, diet, habitat use, health parameters among others), collecting data at long-term and throughout experimental work.

We have outlined some clear gaps of knowledge of polar systems functioning, interactions, and feedbacks. Only by filling those gaps, we will be able to design and implement sound, effective and environmentally friendly policies to protect these fragile but vital ecosystems, and to mitigate the negative effects of the ongoing anthropogenic impacts. Here, we list nine key-challenges to highlight the gaps of knowledge that currently exist in the different spheres of polar systems (atmosphere, cryosphere, oceans, biosphere, geosphere), and possible ways for tackling them.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Prospective analyses about future research in both Arctic and Antarctica have been recently carried out (ICARP III, 2014, Kennicutt et al., 2015). These analyses have identified a number of relevant questions that should be addressed in the next 20 years to prompt major advances in basic science and develop more effective strategies for adaptation and mitigation of the impacts of human activities. All these questions are directly linked to three of the Sustainable Development Goals defined by the United Nations: 13: Climate Action, 14: Life below water, and 15: Life on land.

The challenges we are presenting in this chapter aim to address the following key questions, which are a synthesis of current high-impact priorities included in Kennicutt et al. (2015) and international polar assessment reports (ICARP III 2014):

2.1. Observations for monitoring, understanding and forecasting

- Establishing observatories as part of observing systems to provide comprehensive measurements over the PR.
- Supporting the development and deployment of new technology to improve our understanding of the physical, ecological and social environments of the PR.

2.2. Global change in PR and associated impacts

- Assessing and understanding the causes of rapid Arctic and Antarctic amplification, including their impacts on atmosphere and ocean circulation and connections to the global climate system.
- Constraining future changes in polar subsystems (marine and terrestrial ice, polar ozone, etc.) and their impacts on the global climate system.
- Benchmarking teleconnections, feedbacks, and ranges of climate variability at decadal and longer temporal scales, their role in the ice sheet response for the last millennia, and their potential to forecast short- and long-term climate trends and impacts on PR.
- Assessing the diverse impacts of climate change and human activities on PR biodiversity and its consequences for ecosystem goods and services and societal impacts.
- Characterizing what is the exposure and response of polar organisms and ecosystems to atmospherically deposited contaminants (e.g. black carbon, mercury, sulphur, POPs, etc.), and determining the perturbations on their sources, biogeochemistry and fate over time.
- Determining which are the impacts of changing seasonality and transitional events on terrestrial and marine polar ecology, biogeochemistry and energy flow, and how changes in extreme events can be used to improve our understanding and forecasting of these impacts.
- Assessing what are the synergistic effects of multiple stressors and environmental change drivers on PR organisms and ecosystems, how the threshold transitions will vary over differential spatial and temporal scales and how they will impact ecosystem functioning and linkages between marine and terrestrial ecosystems under future environmental conditions.
- Determining which food webs are most vulnerable, and which organisms are more likely to disappear.

- Characterizing what is the genomic basis of adaptation in PR organisms and communities.
- Determining how invasive species and range shifts of indigenous species will change polar ecosystems, and how climate change will affect the risk of spreading emerging infectious diseases to PR.

PR and global climate changes

- Enhance understanding and representation of processes of the fully coupled climate system (atmosphere-ocean-ice-permafrost-ecology) at several spatial and temporal timescales, to better constrain future projections.
- Improve our understanding of the physical interrelation between the climates of PR and extra- polar ones to assess global drivers of PR and remote impacts of PR changes.
- Understanding how climate change will affect the physical and biological uptake of CO_2 by the Polar Oceans.
- Determining how changes in freshwater inputs will affect ocean circulation and ecosystem processes.

3. KEY CHALLENGING POINTS

3.1. Stratosphere-troposphere coupling and polar ozone

It is now well established that the stratosphere plays an important role in tropospheric climate, mainly due to ozone loss and recovery, changes in stratospheric water vapor and stratosphere-troposphere (ST) dynamical coupling (Figure 2).

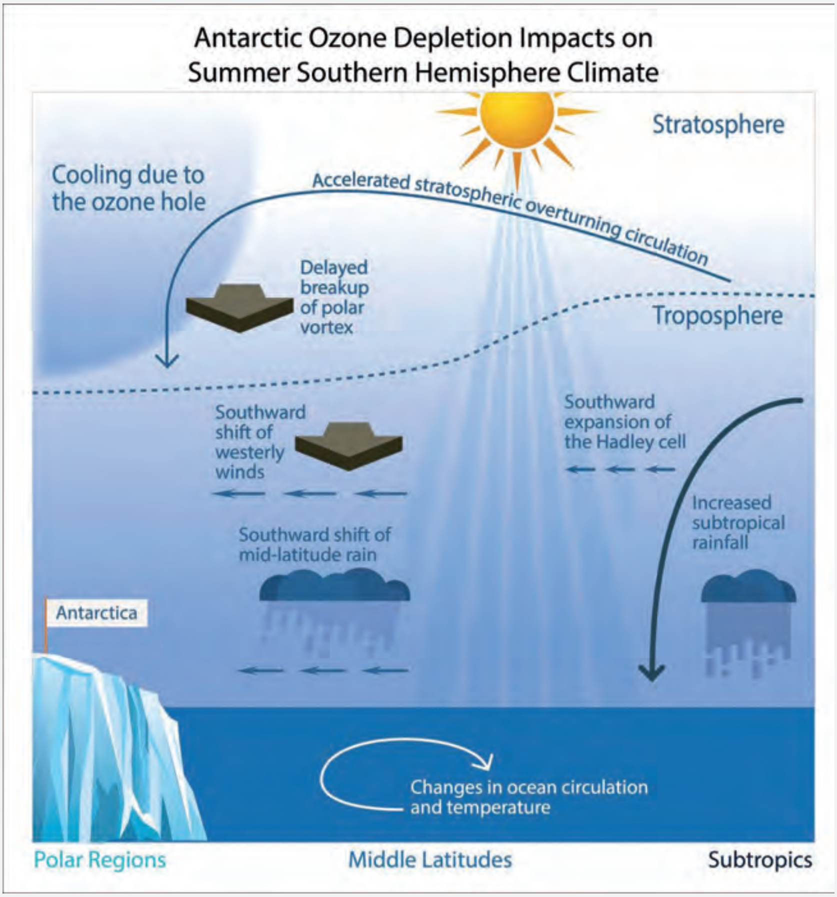
Salient examples of the latter are abrupt temporary warming events of the polar winter stratosphere called Sudden Stratospheric Warmings (SSWs). The associated weakening of the polar vortex (westerly winds in the polar winter stratosphere) can propagate to the troposphere and cause longlasting temperature and precipitation anomalies (e.g. Kidston et al. 2015). Therefore, SSWs are powerful sources of subseasonal-to-seasonal predictability, mainly in the extratropics of the Northern Hemisphere (NH; Challenge 3 in Thematic 12). The modulation of the NH polar vortex by internal modes of variability, such as the Quasi-Biennial Oscillation (QBO) or El Niño-Southern Oscillation (ENSO) also promotes ST coupling and remote teleconnections to the Euro-Atlantic sector, therefore representing additional sources of winter predictability. However, the diversity of drivers of polar vortex variability, their co-occurrence in the short observational records, and relative efficacies in stratosphere-troposphere coupling are major issues. Additional challenges concern the stratospheric vs tropospheric control of SSWs, the dissimilar tropospheric effects of SSWs, the mechanisms of downward propagation and how they are influenced by the initial state of the troposphere and stratosphere.

Despite years of modelling improvement in the stratosphere, no consensus exists on future changes in the NH polar vortex and ST coupling (e.g. Ayarzagüena et al. 2018). State-of-the-art climate models project a tendency to a weakening and longer-lasting NH polar vortex in the future, and slight frequency increases in SSWs. However, there are large discrepancies in the magnitude and sign of the projected changes across models, arguably due to structural differences (e.g. gravity wave parameterizations). Despite the lack of robust changes, many individual models show significant stratospheric responses to climate change, with associated effects in surface projections. Understanding and reducing this uncertainty is critical for narrowing regional climate projections (see also Challenge 2 in this Thematic).

Stratospheric ozone has also important climate implications. Lower stratospheric cooling due to spring Antarctic ozone loss (caused by anthropogenic emissions of ozone depleting substances, ODS) has been the dominant contributor to the observed changes in the summer atmospheric circulation of the SH (e.g. WMO 2018), but with larger uncertainties concerning the impacts in the southern ocean and Antarctic sea ice (Challenge 6 in Thematic 13). The comparatively smaller spring ozone depletion in the Arctic does not lead to robust surface responses in the NH. However, its large interannual variability can cause short-term effects on surface climate (e.g. Calvo et al. 2015). As Arctic ozone is largely determined by the strength of the polar vortex, disentangling their surface effects is of paramount importance for subseasonal-to-seasonal forecasts.

Following the Montreal Protocol and its Amendments, concentrations of ODS are declining since the late 1990s, despite a recent unexpected increase in CFC-11 emissions (WMO 2018). The detection of polar ozone recovery trends is more challenging because of limitations in availability, length and consistence of observations in the stratosphere, the large internal variability and the influence of multiple external forcing (e.g. volcanic eruptions, solar activity, and anthropogenic greenhouse-gases, GHGs). Still, large amounts of ozone

FIGURE 2–Schematic illustration of Southern Hemisphere climate impacts in austral summer associated with Antarctic ozone depletion. Ozone depletion has cooled the Antarctic stratosphere, leading to a delayed breakup of the stratospheric polar vortex and an accelerated stratospheric overturning circulation. Impacts have extended into the troposphere with the region of strong westerly winds and associated rainfall shifted southward, affecting the ocean circulation. The subtropical edge of the tropical circulation has also expanded poleward, leading to reduced precipitation in mid- latitudes and enhanced precipitation in the subtropics. Credit: Figure 5-12: Karpechko, A.Yu. and A.C. Maycock (Lead Authors), M. Abalos, H. Akiyoshi, J.M. Arblaster, C.I. Garfinkel, K.H. Rosenlof, M. Sigmond, Stratospheric Ozone Changes and Climate, Chapter 5 in Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project – Report No. 58, World Meteorological Organization, Geneva, Switzerland, 2018.



depletion have been avoided, and a recovery of spring Antarctic ozone has been detected over 2000-2016 (WMO 2018). The drivers of future ozone trends are ODS, but also well-mixed GHGs (CO2, CH_4 and N_2O), whose radiative effects promote ozone production and poleward transport. ODS play a larger role in Antarctic ozone recovery, while Arctic ozone recovery is more affected by GHGs, with an earlier return to historical values (WMO 2018). However, ozone recovery rates are highly uncertain and scenario dependent. Some well-mixed GHGs interfere in ozone chemistry, while ODS, their substitutes (HFCs, hydrofluorocarbons) and ozone itself act as GHGs. Feedbacks between chemistry and climate also modulate ozone trends and represent foremost issues. For example, ozone recovery partially offsets the radiative effects of GHGs, and GHG-induced changes in transport affect the lifetime of ODS.

Uncertainties are also evident in the impacts of long-term ozone changes on surface climate. In the SH, stratospheric ozone recovery is expected to drive future circulation changes that oppose those of increasing GHGs (WMO 2018). The NH surface responses to Arctic ozone trends remain less explored, even when Arctic ozone is projected to surpass historical levels, yielding a super-recovery. Negative chemistry-climate feedbacks, involving a reduced surface warming, may occur due to ozone-induced changes in stratospheric water vapor. While this feedback is robust, its importance varies among models, representing a major source of uncertainty in future projections (e.g. Chiodo and Polvani 2019).

In summary, there are still important gaps in the understanding and quantification of ozone evolution and its effects on surface climate at intra-seasonal and long-term scales. Major challenges involve feedbacks between ozone chemistry, radiation and atmospheric circulation. High-quality observations in the stratosphere, improved process-based understanding of the interaction between ozone and climate, and the role of natural and anthropogenic factors, along with improved modelling capacities would bring significant advances.

3.2. Polar climate variability and trends as indicators of global change

The recent temperature fluctuations are provoking a large array of impacts in all implied polar spheres (i.e., cryosphere, biosphere, oceans), especially in the polar atmosphere, where the recent warming is significantly altering

Earth's energy budget, temperature gradients, and air chemistry and circulation (Kennicutt et al., 2014; Tesar et al., 2016).

Changing the atmosphere energy budget can affect the main modes of climate variability (North Atlantic Oscillation / Arctic Oscillation (NAO/AO) for the NH and Southern Annular Mode (SAM) for the SH), with remarkable consequences for humans and ecosystems at mid-latitudes. In addition to changes induced by anthropogenic (Challenge 1 in this Thematic) and natural external forcings (Challenge 3 in Thematic 12), these modes of climate variability also experience internal fluctuations and hence exert their influence at several temporal scales, from daily to multidecadal ones. Large efforts have been conducted to describe these modes of climate variability in the NH and understand the associated impacts at seasonal and interannual timescales in the Arctic, through the use of instrumental meteorological and, more recently, satellite datasets. Comparatively, little is known about their SH counterparts affecting the Antarctica due to the poor spatial coverage of long-term instrumental measurements, as a consequence of intrinsic logistical and technical difficulties to maintain equipment in these remote and harsh areas. A long-term funding program to support this long-term monitoring should be promoted, as meteorological instrumental datasets are of paramount importance to characterize and understand recent climate trends.

Furthermore, there is poor understanding of the long-term evolution of these modes of climate variability in both poles before the mid-late twentieth century, which is essential to characterize extreme events and anomalous periods, place recent changes in a historical context and anticipate near-future consequences on PR. Efforts following some recent attempts to characterize their evolution for the last several millennia are strongly encouraged (Hernandez et al., 2020). Achieving this requires participation of CSIC researchers in collaborative national and international initiatives to obtain sedimentary records to reconstruct the long-term evolution of the polar climate modes of variability (see also Challenge 1 in this Thematic).

Climate change can also affect other extratropical (the Scandinavian (SCAND), the East Atlantic Pattern (EA)) and tropical (El Niño - Southern Oscillation (ENSO)) modes of climate variability, which, in turn, modulate the polar ones. Understanding the complex interactions between these modes of climate variability at several timescales is also challenging to better understand the past, present and future evolution of PR.

3.3. Monitoring polar changes with satellites

Processes involving the cryosphere play a central role in PR and remain an important source of uncertainty in projections of future climate change. Therefore, improved understanding of the cryosphere in a changing climate is clearly a "Grand Challenge", as stated by the World Climate Research Program (https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview). A key knowledge gap relates to the impact of thawing permafrost on the global carbon cycle. The magnitude of the positive feedback between a warming climate and the emission of greenhouse gases from natural sources, particularly methane emissions from thawing permafrost, is only starting to be systematically studied. Some experts believe that the effect of this feedback may be catastrophic (tipping point), while others are sceptical about its significance. Drawing the full picture is complicated due to the limited information on the quantity and form of carbon sequestered in permafrost, the inadequate knowledge of arctic biogeochemistry, and the insufficient understanding of the interactions among the terrestrial cryosphere, hydrology and vegetation in northern high latitudes.

In situ observations at both poles are scarce, and satellites offer an opportunity to monitor and understand high-latitude regions. In recent years, the quality and the quantity of remotely sensed data have increased exponentially, allowing comprehensive monitoring of the changes that the PR are undergoing. In terms of number of observations, satellite data dominates by far the volume currently employed for operational mapping tasks and ingested by data assimilation systems. Sea ice thickness and extension, as well as glacier melting rate, are some of the main parameters to monitor changes in PR. However, there are still some data and research gaps, which represent a challenge for the routine integration and assimilation of existing and potential new space-based products into forecasting models. Some of the identified gaps are summarized below (as identified in the context of Kepler EU project, https://kepler-polar.eu/):

- More in situ data in PR are required, in order to improve and validate retrieved parameter and products derived from remote sensing data.
- Resolution and accuracy of the current satellite observations should be enhanced to improve our knowledge on the spatial and temporal changes ongoing on the poles.
- Assessing the melting rates at ice sheets and glaciers with good accuracy is fundamental to predict the GMSL rise (IPCC, 2019).

- The main permafrost variables (i.e. ground temperature profile, active layer thickness, permafrost extent/fraction) cannot be directly observed from space (Bartsch et al., 2014). However, in some cases they can be determined from a combination of modelling and satellite data products. More effort is needed to enhance the permafrost monitoring with remote sensing data.
- Snow depth on sea-ice is very poorly measured from space, while it has a large impact on the sea ice thickness computation, among others.
- The ice thickness is also a very important essential variable with large impact on climate modelling but the uncertainty of satellite measurements is large, especially for evaluation the thickness of thin ice.
- During melting periods, and in the presence of melt-ponds, the accuracy of the estimates of sea ice concentration derived from microwave radiometers considerably decreases. Efforts are required for algorithms to achieve better observations of the ice surface fraction. In parallel, forecast models must be developed to ingest the ice surface fraction.
- After quality tests and validation, these data should be ingested by comprehensive assimilation schemes to feed global reanalyses and Climate Services (Challenge 2 in this Thematic).

3.4. Past ocean dynamics and ice stability under warmer than present conditions

About a third of the Antarctic Ice Sheet (AIS) is a "marine-based ice sheet", which means it rests on bedrock that is below sea level with most of the ice-sheet margin terminating directly in the ocean. Due to the major impacts that AIS melting would have on GMSL, it is also a 'tipping point' (see also Challenge 6 in Thematic 13). Marine-based ice sheets can experience non-linear and rapid melting and calving due to instabilities. Ice shelves in contact with bathymetric features on the sea floor or confined within embayments provide back stress (buttressing) that impedes the seaward flow of the upstream ice and thereby stabilizes the ice sheet. Ice shelf thinning and loss of buttressing can initiate grounding line retreat. If the grounding line is located on bedrock sloping downwards toward the ice sheet interior, initial retreat can trigger a positive feedback, resulting in a self-sustaining process known as Marine Ice Sheet Instability (MISI). The disappearance of ice shelves may allow the formation of ice cliffs, which may be inherently unstable. This ice cliff failure may also lead to ice sheet retreat via a process called Marine Ice Cliff Instability (MICI), that has been hypothesized to cause partial collapse of the marine-based parts of the Antarctic ice sheet within a few centuries (e.g., DeConto and Pollard, 2016).

Key challenges to be addressed include: 1) to understand what processes lead to the destabilisation of ice shelves and ice sheets and how do these relate to global mean atmospheric and sea surface temperature; 2) as climate continues to warm the question becomes, when will we see amplified surface warming around Antarctica, and if there is a temperature threshold for increased mass loss of the land-based ice sheet; 3) what the influence of global ocean circulation is, via a modified thermohaline circulation (THC) and the Antarctic Circumpolar Current (ACC), on the flux of heat across the continental shelf into grounding lines and ice shelf cavities, and 4) the role of associated dense saline water and freshwater feedbacks, including sea-ice, ocean stratification and polynyas on the THC and ACC. To generate this new detailed knowledge of the current state and processes that control ice sheet dynamics and related GMSL changes it is necessary to obtain geological, geophysical, and ideally direct measurements (e.g., CTDs, gliders, ROVs, etc) from beneath ice shelves, ice streams, outlet glaciers and from offshore, coast and open ocean. These data will constrain for example sub ice-shelf bathymetry, ice stream basal conditions, grounding line retreat histories, oceanic current dynamics, past sea surface temperatures, present water masses temperature and salinity profiles, and sea ice distribution, among others.

In particular, marine geophysical and sediment records inform us about ocean and ice sheet-ice/ice shelf variability under different climate conditions and states. These records can provide rates and patterns of ice sheet retreat during past deglaciations and the sensitivity of the ice sheet to past warmer climates (i.e., higher CO_2 concentrations, higher surface temperatures and/or stronger orbital forcing). Because the magnitude of climate forcing projected for the next century has not been experienced by Earth for more than 3 million years, paleoclimate reconstructions of past Greenland and Antarctic ice sheet responses are key in providing critical insights into their future behaviour. The influence of both ocean dynamics and solid Earth deformation on ice sheet dynamics are yet to be assessed against these past policy-relevant warm climates. In addition, warm intervals are not all the same. There were "warmer-than-present" intervals in the past coinciding with higher atmospheric CO_2 concentrations, but also times when CO_2 concentration was at pre-industrial levels, and orbital forcing was more important, causing warming that reduced ice volume dramatically and increased GMSL (Dutton et al., 2015; Wilson et al., 2018). Still, sedimentary core records of past ice sheet change provide key constraints on the long-term (multi-centennial to millennial) cryospheric response to climate and ocean conditions different from today. They capture the 'end-game' scenario that incorporates Earth system feedbacks across timescales (e.g. Colleoni et al., 2018), allowing a more clear picture of the full equilibrium shift (long-term commitments) that might occur under perturbed environmental conditions. Sedimentary records also provide details of ice-ocean sediment interactions and, together with simulations of oceanic circulation coupled to dynamic ice sheet and Earth deformation models grounded in an observation-based understanding of modern processes, provide powerful insights into how the ice sheets responded in the past and will respond in the future.

3.5. Impact of anthropogenic pollutants in the polar regions

The number of chemicals identified in environmental samples using emerging instrumental techniques such as improved high-resolution mass spectrometry is steadily increasing, and better tools have been developed to investigate their combined effects and mechanisms of toxicity. Environmental chemists and toxicologists have moved beyond detecting and quantifying single chemicals to characterize complex mixtures of chemicals in the environment and even delineate their potential effects in organisms and their food webs. Given the clear relevance of mixtures and the fact that thousands of chemicals are occurring in the environment, a shift in the existing regulatory paradigm toward mixture effects is urgently needed (Kortenkamp et al., 2018). In addition, determining the exact impact of organic contaminants on polar ecosystems, or forecasting future scenarios is not yet possible due to the insufficient number of studies and the current lack of representative, suitable and reliable data for the overall polar environments. Contrary to the Arctic, where long-term monitoring data on POPs allow us to investigate temporal trends, data in the Antarctic are much more scarce. Advances in these issues would bring increased capacity of environmental monitoring and diagnostic tools needed to contribute to understand the environmental fate and potential hazards associated with the accumulation of anthropogenic pollutants in the polar environments, or climate driven remobilization of legacy pollutants, and to reduce and prevent the main negative impacts of pollution in the polar ecosystem services. To achieve this, the following challenges should be addressed:

Developing novel diagnostic tools for environmental detection and monitoring of pollutants, and performing long-term observation efforts to track their trends.

Understanding the harmful effects of mixtures of pollutants on the polar biota and ecosystem function in a real scenario based on a multi-stressor food web level approach.

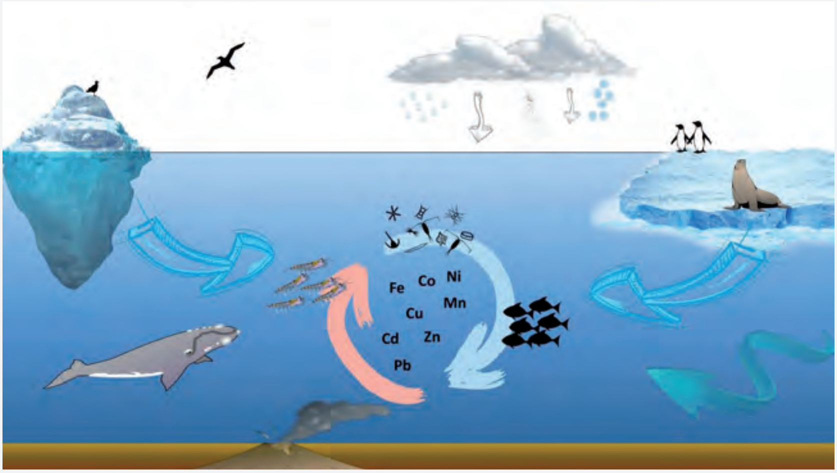
3.6. Biogeochemical cycles of trace metals in the changing Polar Oceans

The Southern Ocean is responsible for the uptake of around 75% of the ocean storage of anthropogenic heat and around 40% of the storage of anthropogenic carbon (Ludicone et al., 2016). Many areas of this ocean are considered as "high-nutrient, low-chlorophyll" (HNLC) regions, where phytoplankton stocks are unable to fully assimilate the high N and P concentrations available in surface waters, and TMs, particularly Fe, play a key role controlling phytoplankton productivity and community structure (Sunda, 2019). Our understanding of the biogeochemical cycles of TMs and their influence on the oceanic productivity in Polar Oceans is still very limited, and changes in the biological productivity by global warming increase further the complexity of these cycles (see also Challenge 6 in Thematic 13).

External sources of TMs to the Antarctic waters are typically low and are not well constrained. Some works suggest the importance of advection of water masses enriched in TMs following contact with continental margins, in addition to atmospheric deposition to surface waters and inputs from hydrothermal vents to bottom waters. In the Arctic Ocean dominant sources of TM include ice melting, atmospheric deposition, river discharges and/or oceanic water mass exchange (Tovar- Sánchez et al., 2010). Recent works have demonstrated that biological recycling is considered an important mechanism in the PR for concentrating and retaining metals in the surface layer waters (Tovar-Sánchez et al., 2007). Until recently, the primary biogeochemical role of marine animals was considered to be as consumers of carbon, converting it into fast-sinking faecal material and returning it to the atmosphere through respiration. However, a number of recent studies suggest that polar marine animals (e.g. krill, penguins, whales) are part of a positive feedback that retains and transports nutrients and TMs to the surface waters, thus enhancing primary productivity and stimulating carbon export (Figure 3).

Therefore, there are a number of sources and processes that control the biogeochemical cycles of trace elements in the polar oceans (i.e. ice melting, atmospheric deposition, biological recycling, etc.) that affect marine primary productivity and ecosystem, and that need to be monitored in order to assess

FIGURE 3–Schematic representation of the biogeochemical cycle of trace metals in the Polar Oceans.



how they are affected under different global change scenarios.

3.7. Tracking pelagic-benthic coupling in the warming cold

Ongoing atmosphere and ocean warming are accelerating glacier melting and consequently increasing fresh water, nutrient and sediment inputs into the water column adjacent to glacier fronts. These processes impact on the biologically mediated atmospheric carbon sequestration and its subsequent incorporation into the sedimentary column, which eventually ameliorate global warming (Isla et al., 2004). Glacier meltwater runoffs can stimulate primary and secondary production; however, intense sediment discharges can clog zooplankton organisms and bury benthos, drastically limiting carbon transfer to the open sea and higher trophic levels and its long-term accumulation in the seabed (Fuentes et al., 2016; Sahade et al., 2018). The rate and extent of all these processes is not completely clear yet, even more when considering other changing and influential environmental factors such as wind and water currents (Isla et al., 2009; Isla et al., 2019). A comprehensive picture of this changing scenario will enable the scientific community to accurately assembly polar and global carbon budgets, fundamental to model and predict future climatic scenarios and properly assess the ecosystem services that the polar regions provide.

3.8. Understanding vulnerability and resilience of Polar aquatic and terrestrial microbial ecosystems to climate change

Warming and ice melting of PR are translated into variations in the composition, activity and diversity of microbial communities, which will have an impact on changes in the food chain and on the life and diversity of polar organisms (Smetacek and Nicol, 2005). In addition, glacier retreat is generating wide expanses of land, which after centuries or millennia covered by ice, are being exposed to the environment and therefore susceptible of colonization through primary succession processes (Garrido-Benavent et al., 2020). Indeed, we have already a fairly amount of information on the biomass and diversity of microorganisms during the warm season, either from natural observations (Vaqué et al., 2017) and experimental approaches in aquatic (Vaqué et al. 2019) and terrestrial systems (Benavent-Gonzalez et al., 2018). Recent reviews emphasize the role of polar microbial and lichen communities as excellent bioindicators of climate change (Maranger et al., 2015; Cavicchioli et al., 2019; Sancho et al., 2019). Nevertheless, the existing diversity of surveys at PR correspond to sporadic analysis at different locations, making difficult to gain insight in specific responses. Likewise, and more concerning is the scarcity or lack of data in the sea ice and underground ice during winter for both aquatic and terrestrial microorganisms. Furthermore, information about microbial community stability and resilience to climatic change is lacking.

We seek to have an ample view of the consequences of the global change in polar microbial communities' resilience and functioning. Thus, a plan for identifying and systematically monitoring microbial, biogeochemical and physicochemical indicators should be established. To achieve this, periodic surveys of microbial community structure at representative locations of PR, in parallel to geochemical and microclimatic parameters recording, must be implemented. Characterization of microbial responses to environmental disturbances can help us to evaluate potential future changes. Potential indicators that could be implemented might be related to phytoplankton biomass changes by monitoring chlorophyll concentration via satellite all year round, although they would require challenging monitoring capabilities. Furthermore, indicators of changes in microbial abundance and distribution associated to environmental changes in sea ice, aquatic and terrestrial ecosystems by the generation of time series in one or various established representative sampling areas in Antarctica (i.e. Livingston and Deception Islands) and Arctic can also be developed. This would require monitoring microbial abundance and activity, biogeochemical and physico-chemical parameters, microclimate conditions at sampling terrestrial points, and of cryptogrammic covers extension for successive years. A third set of indicators might be related to annual and seasonal changes in taxonomic and functional diversity patterns of representative microbial ecosystems such as sea surface microlayer, sea ice, glacier forefields, soils, rocks, and cryptogrammic covers. This monitoring will be performed using different cutting-edge molecular biology techniques: i) Metabarcoding and/or metagenomics analyses to all the samples, and metatranscriptomics analyses when environmental disturbances occur; ii) Specific throughput genome sequence analyses for different aquatic and terrestrial microbial communities in selected scenarios and samples.

3.9. Polar wildlife as indicators of global change

Wildlife is a key component of the ecosystems on which the effects of global change have largely been described (IPBES 2019). Therefore, it should be a crucial part of a set of indicators for monitoring environmental changes. Polar wildlife is characterized by its low diversity in comparison with temperate or tropical environments where the number of species is much higher. For instance, only the 2% of the global fauna can be found in the Arctic (Matveyeva and Chernov 2000). This is even more remarkable in Antarctica due to its geographical isolation, where for instance, there are only one species of insect or 46 species of birds, in contrast with the 3200 and 190 species of the Arctic, respectively. Differences between both PR are also notable in the biomes used by some organisms, since there are no terrestrial vertebrates in Antarctica while in the Arctic both terrestrial and marine mammals are components of its fauna. The low diversity of animals and plants implies simpler food webs in these ecosystems, which make them more susceptible to high impacts by alterations in single components. Moreover, polar organisms are adapted to their specific conditions of low temperature, showing narrow ranges of tolerance and making them especially fragile and vulnerable (Peck et al 2004).

The analysis of the ecological consequences of a changing environment and the understanding of the resilience of its biotic components are required to respond to the challenges posed by global change. Such responses need to be based on a long-term data collection and monitoring of population trends, status, pattern and processes (Taylor et al. 2020). However, even the most necessary information, that is, trends and status, is only available for a few well-known Arctic vertebrates (i.e. caribou, muskoxen, beluga, geese and seabirds, CAFF 2013). The situation is even worse in the Antarctic, with fragmented information available for few species of seabirds and marine mammals. Developing a set of indicators

FIGURE 4—Landscape, wildlife, flora and microorganisms present in the Polar Regions.

for wildlife to monitor the deep environmental changes of PR is, therefore, a pervasive challenge since the last decades.

A first required step is the identification of key species that can be considered sentinels of the environment. These species must meet several characteristics besides easy sampling, such as responding to human activities, exhibiting clearly identifiable responses to environmental changes, affecting the functional structure of biotic interactions (i.e. food web), and showing enough abundance, wide geographic distribution (Hazen et al. 2019). The second step is to define key indicators of ecological change which should be integrative, easily measured, time-varying, sensitive to stress on the system, and with predictable and smoothed responses to stress (Dale and Beyeler 2001). Moreover, as major drivers of polar changes have a global dimension, indicators must consider the type and magnitude of the impacts, as well as the resilience of species and/or processes, considering mitigation strategies at both regional

FIGURE 5—Available infrastructure, equipment and working areas in the Polar Regions.

and global scale. In general, such indicators should include information about population abundance, breeding success, mortality, habitat use, food resources, movement patterns (i.e. dispersion/migration), physiological functions (i.e. thermoregulation) and health status (immune response, parasites/pathogens, diseases, contaminants).

Our knowledge about the wildlife as indicators of environmental change in PR is still far from being acceptable. There is only information of few species and populations, restricted geographical areas, short periods of time and few biological traits. Recent technological advances in different aspects, such as bio-logging, remote sensing, automatic recording equipment, omics techniques and modelling, among others, should be incorporated to traditional techniques, and supported by the establishment of long-term monitoring programs. Ultimately, this challenge will allow us a better understanding of the impact of global change and to predict future environmental scenarios in PR.

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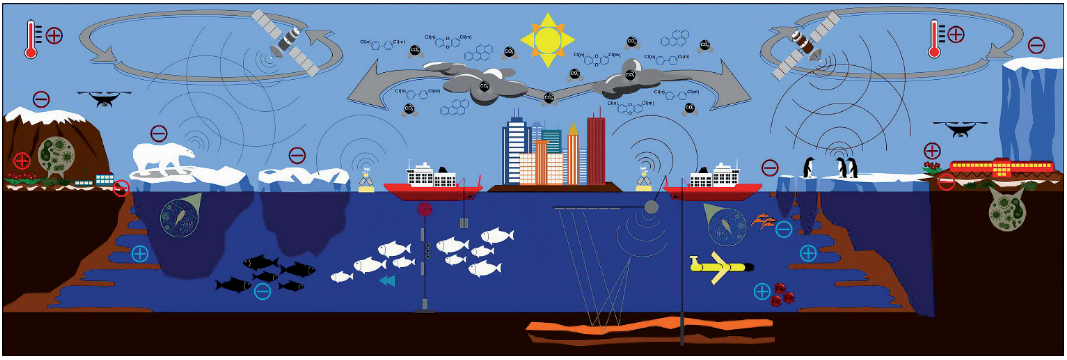
ACADEMIC SLIDE

GLOBAL CHANGE AT POLAR REGIONS—Main threats currently affecting the Polar Regions (PR), and some of the main techniques employed to characterize these threats. Minus signs indicate decline (i.e., wild life and sea-ice) whereas plus signs mark increase (i.e., air temperature and invasive alien species). Horizontal arrows indicate transport towards PR.



DISSEMINATION SLIDE

GLOBAL CHANGE AT POLAR REGIONS

CHALLENGE 5

ABSTRACT

Human activity on natural systems to maximize their productive function is one of the major causes of global change, and we face an increase in the demand of food production due to a growing population and changing dietary habits. At the same time, there is growing evidence that climate change (increase in temperature and occurrence and intensity of extreme weather events, changes of rainfall pattern, rise of CO_2 and other greenhouse gases emissions) in combination with other human-driven changes will impact on managed systems reducing production, modifying composition, altering proper functioning, and affecting extension and geographical distribution. Therefore, the development of actions towards more sustainable, climate-proof and resilient production systems becomes an unavoidable societal commitment.

In this chapter we discuss four blocks of key challenges helping to address such commitment, though (i) a greater understanding of the sensitivity of managed ecosystems to global change and an increased capacity to anticipate future impacts, (ii) reduction of the contribution of managed systems to global warming through the deployment of low-carbon production systems and the enhancement and maintenance of carbon terrestrial pools, and (iii) the development of systems that are less vulnerable to the effects of global change. Successfully tackling the proposed challenges will result in the development and implementation of scientifically sounded policies that address climate, environmental and development issues.

KEYWORDS

soil carbon | forest | wildfires

land-based mitigation

climate change adaptation

agricultural systems | aquaculture | livestock

CHALLENGE 5

IMPACT OF GLOBAL CHANGE ON MANAGED ECOSYSTEMS

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1. INTRODUCTION AND GENERAL DESCRIPTION

Climate change, combined with other global stressors, such as a growing population, health, food and water security, soil degradation, and rising consumption in an ever more interconnected world, are posing significant threats to the integrity and functioning of natural and managed ecosystems and its capacity to support human livelihoods in a globalized world (Herrero and Thornton, 2013; Steffen et al., 2015, Marques et al., 2019). Critically important, impacts on food production systems (cropping, livestock and aquaculture) threaten our capacity to maintain food security and increase by 50 % food production to feed the growing population by 2050 (Porter et al, 2014).

Changes in global temperature and precipitation patterns, as well as extreme events are already affecting crop yield and quality of agricultural and forest systems worldwide. Besides these direct climatic impacts, indirect effects on water availability, land degradation and soil health, changes in crop suitability and shifts of cultivation areas, emergence and spread of pests and diseases, together with biodiversity decline and pollinators loss, will risk the capacity of crop and forest systems to sustain the growing demand of food over the last decades (Mbow et al., 2019). Livestock systems are also being impacted as consequences of global warming and changing patterns in precipitation.

Temperature affects most of the critical factors of livestock production, such as water availability, animal production and reproduction, and animal health. Moreover, increases in aridity will impact the production of pastures for livestock herbivores grazing in extensive systems in many regions across the globe. Climate changes are also expected to indirectly impact the livestock through changes in feed quality increases in CH_4 and antibiotic resistance genes, as well as through microbial pest and diseases outbreaks (Rojas-Downing et al., 2017). On the other hand, aquaculture is one of the fastest- growing food-producing sectors in the world, and this activity is tightly linked to freshwater, brackish and marine waters depending on the countries and water resources. Aquaculture production will be affected by both direct and indirect climate change drivers both in short and long terms. Increase in temperature, heat waves ocean acidification, toxic algae, diseases, and other drivers (sea level rise, more intense and frequent storm events, eutrophication and pollution) will pose an unprecedented risk to aquaculture systems (Blanchet et al., 2019, Froehlich et al., 2018) .These negative impacts could be partially offset by new development opportunities in areas where current production is low.

All these points claim for the development of effective, sustainable and resilient food production systems that ensure their capacity to support human well-being. Building production systems resilient to multiple direct and indirect climate driven impacts will be fundamental for humankind, and will require taking concerted adaptation and mitigation actions. Adaptation is highly context-specific, and no single approach for reducing risk is appropriate across all regions, sectors, and settings. Strategies for adaptation include, but are not limited to, higher quality impact assessment methods and the development early warning systems; optimizing the use of more tolerant species; harnessing genetic variability and biodiversity; water management including agronomic practices to reduce water losses, managing animal's diet and monitoring and managing the spread of pests and diseases (European Environment Agency, 2019). Mitigation in the Land related sector (AFOLU thereafter: agriculture, forestry and other land uses) is key to achieve ambitious goal of 2015 Paris agreement of limiting global warming 2 °C below of pre-industrial level, because it was responsible for about 10–12 % of global greenhouse gases (GHG) emissions in 2010. This sector is the largest contributor of non-CO_2 GHGs (including methane), accounting for 56 % of non-CO_2 emissions in 2005 (Tubiello et al., 2015). Mitigation pathways to reduce the carbon footprint of AFOLU sector are related to the improvement of production system and unlocking the potential of carbon sequestration in soil and biomass.

Biomass and soil carbon stocks in terrestrial ecosystems are currently increasing but they are vulnerable to loss of carbon to the atmosphere as a result of land use changes and the projected increases in the intensity of storms, wildfires and land degradation. Croplands store more than 140 Pg C in the top 30-cm soil depth, the most relevant layer for agricultural production (Zomer et al., 2017). This amount accounts for 19% of the global soil C stocks estimated at this depth (Jackson et al., 2017). Protecting and building C stocks in croplands is of paramount importance, as even subtle C losses may represent a substantial contribution to the build-up of the atmospheric CO_2 pool (~750 Pg C; Ciais et al., 2013). As an example, it is well known that the conversion of non-cultivated ecosystems such as forest to croplands typically causes a rapid decline in soil C stocks due to practices such as tillage or inorganic fertilization.

Forests are currently a net sink for carbon at the global scale. It is estimated that intact and re- growing forests currently contain 860 ± 70 Pg C and sequestered 4.0 ± 0.7 Pg C yr–1 globally between 2000 and 2007 (Settele et al., 2014). The future of the interaction between the atmosphere and forests is however unclear. Most models suggest that rising temperatures, drought, and spreads of wildfires and dieback episodes will lead to forests becoming a weaker sink or a net carbon source before the end of the century. Reforestation and deforestation processes over the next decades will play a key role in driving the future of C stocks worldwide (Roe et al., 2019)

The effects of the increase in the frequency of extreme weather events linked or not with other factors can be aggravated by a lack of, or erroneous management, which can expand the impact of climate change in already vulnerable forest ecosystems. For instance, wildfire activity is not only controlled by climate (Pausas and Keeley 2014), it requires ignitions and appropriate vegetation to spread, and these two factors are strongly related to human activities (land use, rural abandonment, afforestation, housing, etc.; Pausas and Fernández- Muñoz 2012). The necessary role of forest and landscape management on preserving forest goods and services in face of global change must be understood by the broad society.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

The effects of climate and others non-climate driven changes on natural resources and food production are already evident. The need to ensure food security in a changing world is recognized by the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). Indeed, many countries have included food production systems under their mitigation and adaptation plans as found in their National Determined Contribution (NDCs) to Paris Agreement. The importance of soil C in mitigating climate change is currently recognized in international political actions such as the 4 per 1000 initiative. Governments committed by the 2015 Paris Agreement to limit global warming to less than 2°C above pre-industrial levels and to pursue efforts to limit the increase to 1.5°C and to adapt to unavoidable changes.

Pursuing effectively this ambitious goal will require to take actions to curb greenhouse gas (GHG) emission and to adapt to unavoidable changes that should be based on an improved understating of the links and causalities between climate events, ecosystems functioning and human-made decision on land and water resources management.

The research path proposed in this chapter aims to (i) identify and fill existing knowledge gaps on the global assessment of the impacts of different scenarios of global change on managed ecosystem, (ii) realize the potential capacity of the food production systems and land sector to reduce GHG emissions; and (iii) strengthen the resilience of the primary production sector to the impacts of global change.

In the next section we propose four key challenges. Each one addresses specific issues to further advance in the scientific understanding of the consequences of global change and how to cope with it. We expect that a successful response to the proposed key challenges will exert a positive impact on:

- Performing more reliable global impact assessment on food production systems by accounting for the combined effects of multiple stressors, and a better knowledge of the vulnerability of the species and the whole system to climate and non-climate related drivers.
- Developing early warning systems and other tools to forecast climate-sensitive events (storms, droughts, pest outbreaks) that allow to take up actions in advance.

- Devising approaches of mitigation based on more robust associations between climate-induced drivers and human-directed drivers of global change to avoid incorrect attribution.
- Boosting the use and management of biodiversity (genetic variability, soil diversity, gut microbes landscape heterogeneity) to adapt to climate change and reduce the footprint of production systems.
- Supporting the adoption of adaptation strategies that deliver co-benefits in terms of climate change mitigation, biodiversity conservation, prevention of land degradation, and water and food security.
- Fostering the adoption of integrated landscape management to deal with land competition issues while securing the provision of ecosystem services in a changing environment.
- Shifting from risk management adaptation practices (mainly at farming and exploitation level) to transformative projects of food production systems.

We also expect that the outcomes of this research have a strong impact on the development of policies and programs to tackle the environmental and development challenges across scales. Food, water and climate are three prominent elements in Sustainable Development Goals (SDGs). Eradicating hunger by 2030 (SDG 2) requires more sustainable food production systems and climate-resilient agricultural practices, which also offer active solutions to decreasing the negative effects of climate change. Food security and land sector (AFLOU) are also critical to other aspects of sustainable development, including poverty eradication (SDG 1), health and well-being (SDG 3), clean water (SDG 6), decent work (SDG 8), and the protection of ecosystems on land (SDG 15) and below water (SDG16).

At European level, dealing with climate change is a key objective of the European Green Deal, the Common Agricultural policy (CAP) and the Farm to Fork Strategy. The proposed new CAP for 2021-2027 has adaptation as a clear objective, and the achievement of the objectives of net zero GHG emissions in the EU by 2050 will be required an increase in carbon sequestration in agriculture and forestry sectors.

Finally, the 3rd work programme of the Spanish National Plan of Climate Change seeks to promote actions to adapt to climate change and reduce vulnerability of sectors. The plan recognizes that knowledge of climate changes impact on primary sector is copious but scattered and with gaps that need to be effectively implemented in plans and programmes.

3. KEY CHALLENGING POINTS

3.1. Understanding the impact of global change on food production systems: cropping, livestock and aquaculture

Advancing modelling of the impact on agricultural systems

Understanding how climate change and land degradation affect current crop production and food security, and the extent to which they will do so in the future is crucial to develop and adopt actions to mitigate and adapt to global change impacts. Our understanding of the relationship between climate change and land degradation with agricultural production is still very limited, in particular when impacts are multiplied or combined with other socio-economics consequences of climate change. On the other hand, attribution of any observed changes to climate trends are further complicated by the fact that models linking climate and agriculture must, implicitly or explicitly, make assumptions about farmers' behavior.

Consequently, we need to increase our knowledge and to improve our capacity to assess current and projected impacts of global change on agriculture and food security (Elbheri et al., 2017). The following lines of research can be identified as a priority:

- Developing complex impact assessment models that (i) evaluate cumulative impact by integrating direct (raising temperatures, changes in rainfall patterns, increase CO_2 concentration in the atmosphere) and indirect (water availability including aspects related to both quantity and quality land health or land use changes) climate impacts (ii) appraise crops suitability, and (iii) simulate multi-crops.
- Incorporate biophysical and socio-economic drivers of crop production and land use on complex integrated assessment models so to (i) enhance the capacity of attribution of projected changes to climatic and anthropogenic changes, and (ii) forecast agricultural land abandonment and land use changes resulting from decrease on profitability and shifting of production locations (cascade effect).
- Modelling the impact of the occurrence of weather extreme events (drought, frost and heat waves) during critical phenological periods and their impact on crop yield and its components.
- Improve our assessments of the impact of future climatic scenarios on crop quality. Although there are growing evidence suggesting a decline in proteins and nutrient content of the crops due to the increase CO_2 concentration, modelling impact on quality is well behind than on

quantity (weights) aspects.
- Ensuring long-term monitoring programs to collect temporal data aiming to understand complex dynamics in climate change and yield production, which are further needed to validate and test impact global change cropping models.

Improving our knowledge on the sensitivity and vulnerability of livestock system to global change

The impact of global change on livestock has received comparatively less attention than the impacts on crop production. Moreover, there is a need of a deeper understanding on the sensitivity of the different factors and the whole production system to individual and combined changes of climatic variables. To advance on this knowledge, we should address the following objectives:

- Assessing the impact of climate change on production and nutritional composition of forage and other fodder crops. It is crucial to map the impact of global change by different geographical areas and crop types to forecast feed yield.
- Assessing the impact of climate change on trophic interactions and sustainability in grazing ecosystems from a comprehensive perspective, including farmers' operational decisions
- Understanding the sensitivity to heat and water stresses of species and breeds at different physiological stages through the identification of the molecular basis of the adaptive mechanisms and their links with reproductive and food efficiency, immunological competence and quality of animal products.
- Understanding the impact of climate change on spread and the life-cycle dynamics of pathogens outside of the livestock host species
- Assessing the cost and effectiveness of adaptation options to the combined impacts of climatic changes. There is a strong need for additional research on integral multifactorial impact assessments

Integrated assessment of multiple stressors on aquatic species

Evidence of the impact of global change, and particularly climate change, on the aquaculture systems is still limited compared with that in other food production systems. Future is needed to progress in an integrated knowledge of the effect of water temperature, dissolved oxygen, acidification, pollutants, and salinity on the growth, nutrition, metabolism, reproduction, immune status and adaptability of the aquatic species. There is a need for long-term experimental studies with multiple stressors, including analysis of different generations and life stages, to assess basic questions such as the role of phenotypic plasticity (within one generation) and also trans-generational adaptation. All already known stressors affect different aspects of the reproduction, growth and health, but in many cases the underlying molecular mechanisms are not known yet. Accurate determination of thermal tolerance on different stages (larvae, juvenile, and broodstock) and the consequences of increased temperature on behaviour and productive traits affecting digestion and feed conversion, health and welfare, stress resilience, nutrient requirements and the use of new raw material as main components of new aqua-feed formulations have not been completed for the main farmed species. Likewise, reproductive capacity is highly dependent on water temperature, and most environmental stressors including raising temperature affect sex steroid profile, which also has an impact on the quality of the progeny through the involvement of epigenetic mechanisms.

In order to predict the impact of climate change on aquaculture the development of coupled climate – biological /ecological models are also necessary. Advances and development of these models will not only contribute to produce early warning systems able to support decision making under the current climate change conditions, but also to predict the impact of climate change on aquaculture activities on the medium and long-term, to evaluate future risks and opportunities and to elaborate adaption plans to ensure food security.

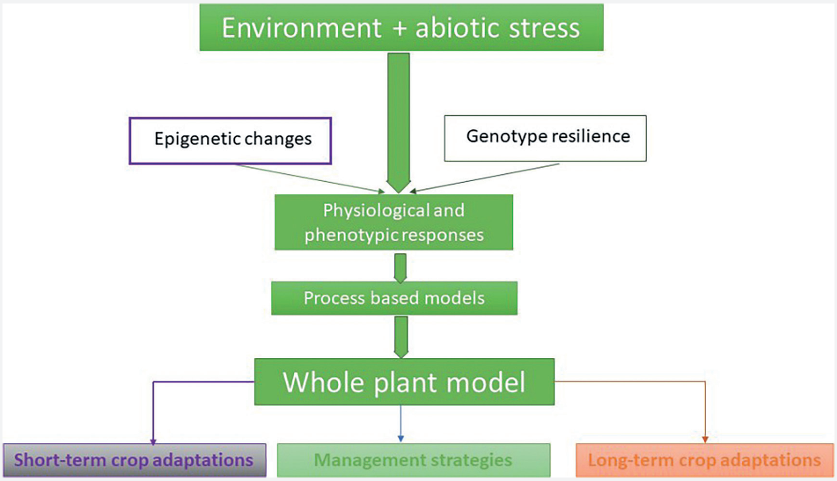
3.2. Fostering resilient and better adapted food production systems

Innovative tools for building resilient agricultural systems: crop management modelling and harnessing soil biodiversity

Adaptation options at farm level combine the use of current genetic resources and breeding programs for obtaining more tolerant crop species and varieties, the development of new crop diversification and rotation strategies, the adoption of advanced agronomic practices including precision farming and modifying crops calendar, and the better management of natural resources. Challenges associated to development and operational implementation of these responses (sustainable intensification, agro-ecology, sustainable land management) are discussed in thematic 6.

Here, we will focus on additional challenges regarding on the development of process-based models (PBM) aimed to design crop adaptation to specific

FIGURE 1–Innovative tools for building resilient agricultural systems: crop management modelling



changing environments and to the use of biodiversity to maintain and increase yield production while minimizing ecological footprint. This framework should result in a combination and integration of biology, technology and computation sciences applied to the whole farming system under study (Figure 1).

Crop strategies are ecosystems context-dependent. Therefore, results obtained for a given Genetic (G) × Environment (E) interactions are often only valid for the local conditions where in these strategies are developed. However when results are extrapolated to other sites many times contrasting results are reported. PBM are increasingly being used for research and application purposes in plant sciences and natural resource management (Holzoworth et al. 2014). Such models integrate the complex interactions of crop eco-physiological processes as they respond to environmental drivers and predict their impact on productivity. The ability of crop models to capture cultivar (or genotype) differences within a crop species in response to environment and management drivers enables simulating the outcome of the complex interactions among genotype, environment, and management (G×E×M), thus allowing phenotypic attributes to emerge as a consequence of model dynamics. PBMs can be applied at different levels, from genes to whole plants. PBM are tools to make physiology and genetics more predictive by bridging the gap between genotype and phenotype. The physiological and adaptive responses of plants to environmental changes are the result of complex interactions between genetic and epigenetic mechanisms that are translated into changes to specific functional traits. By using PBMs, it is also possible to integrate genetic information into plant physiological responses. In addition, PBMs have the advantage that they can be used in Decision Support Systems to simulate crop behaviour and take decisions on crop management practices.

Harnessing the microbiome associated soil and crop species in agricultural ecosystems (i.e., the crop microbiome) will be of paramount importance to promote future healthy and productive agricultural ecosystems in a changing world. In order to unleash the full potential of the crop microbiome aiming to promote healthy and productive crops under future scenarios of climate change and extreme climatic events (e.g., drought) we need (i) to characterize the structure and function of the major crop species (e.g., wheat, rice, corn, potatoes etc.) across wide climatic and vegetation global gradients (e.g., https://www.globalsustainableagriculture.org), and to identify the components and functional capabilities of the crop microbiome; (ii) a better understanding about what, how and why keystone species influence crop production; (iii) to identify what microbial species are cultivable and able to team up with other microorganisms as to create plant probiotics capable of promoting yield production in a global change context, and (iv) to know more about the evolutionary changes in the microbiome of crop species during the domestication process that could help us to identify particular keystone microbial species and traits, which were lost during the domestication process, but that, could now be used to promote plant production under stressed environments.

Agriculture in a drier world: Increasing the efficiency and sustainable use of water resources

Increasing the efficiency and sustainability of the water use by agricultural systems is needed to cope with the double challenge of meeting a higher water demand with less available freshwater resources.

Designing water efficient agricultural systems through the application of agronomic practices that reduce evapotranspiration losses will lower the water consumptive use. Woody perennial crops have often incomplete ground cover leaving part of the soil directly receiving a high radiation regime that increases the evaporative component of the orchard evapotranspiration.

Sub-surface drip irrigation systems eliminate most of the soil evaporation component from the system water balance, and they could be used in cases of water scarcity. In addition, when the volume of applied water needs to be restricted in relation to potential evapotranspiration, decreasing the volume of soil wetted by the drip system, by reducing the number of emitters per tree, can be a useful way to increase the irrigation efficiency.

In fruit trees, there is evidence that high fruit load may enhance the sensitivity of fruit growth to water stress (Berman and DeJong, 1996). Hence, reducing fruit load has been used to mitigate the negative effects of plant water stress, though with important yield penalties. Under low crop demand conditions, a reduced plant photosynthesis rate due to water stress is less detrimental since fruit are the major sink for carbohydrates, particularly during stage III of fruit growth. In addition, lowering fruit load has been shown to reduce plant water use because of a reduction in stomatal conductance via feed-back mechanisms.

Eliminating part of the actively transpiring canopy surface area (such as whole branches) can be also used to help fruit tree survival under extreme drought conditions. It is obvious that this practice has major consequences on the current year tree performance, but at least can guarantee plant survival. In addition, innovative canopy forms should be designed to optimise light interception reducing tree transpiration under soil water limiting conditions. Under a future scenario of reduced water availability, new orchard and vineyard designs might alleviate the impact of drought stress. In this sense, the use of shading nets has been proven to be useful for increasing water use efficiency and even crop performance.

The improvement of water use efficiency at field, or farm level, (maximizing "crop per drop") should be aligned to the optimized sustainable use of water resources at basin level as an element of Integrated Water Resources Management (IWRM). IWRM is a coordinated process focusing on both economic and social issues while protecting ecosystems and ecosystem services at the same time. The IWRM approach has been accepted internationally as the way for efficient, equitable and sustainable development and management of the world's limited water resources and for coping with conflicting demands. This IWRM approach is required for coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Methodologies for integrating climate change adaptation (CCA) into IWRM should be investigated, developing innovative approaches and/or testing existing ones. The IWRM-CCA approaches should be implemented and tested by involving all the potential stakeholders in experimental sites representative of Spanish water conditions in terms of water scarcity, water use efficiency, use of non-conventional irrigation waters (saline and waste), changing climatic conditions, different crops, conflicting use of available waters, as well as need for governance by different authorities, and other relevant factors. Existing simulation models predicting the impact of climate change can be useful tools for developing adaptation strategies. Calibration and validation of these models is necessary to obtain site-specific results in terms of climate change impact and adaptation. These results should be incorporated in the IWRM-CCA approach to develop water allocation strategies aimed at meeting various sectorial water demands under future climate change scenarios and with different socio-economic assumptions.

Better adapted livestock production systems to climate change

Livestock production systems have proved to be resilient to disturbances because of their technical and biological adaptive capacity. None of the less, the magnitude, intensity and pace of projected impacts of global change will make necessary to strengthen the adaptive capacity of the different elements of the system. To devise better adapted livestock systems, we need additional research on:

- Developing early warning systems (EWS) on stresses driven by climatic change and infectious diseases. Increasing the capacity of forecast climate-sensitive diseases outbreak, and the application of responsive measures at the proper time are key factors for a more effective prevention and control.
- Reassessment of current production systems to identify the species, breed and crosses most adapted to local environmental conditions and the production objective and increase diversity. The improvement of animal rearing conditions (shading and sprinkles, ventilation systems) could mitigate the projected impacts of growing of heat and water stresses in arid and semiarid zones. However, an integral assessment of the system will be necessary, including risk analysis and the evaluation of the efficiency in the use of resources (water energy) needed. Some authors argue for using local less productive species but more tolerant to stresses instead of more tolerant strains by breeding non-adapted species.

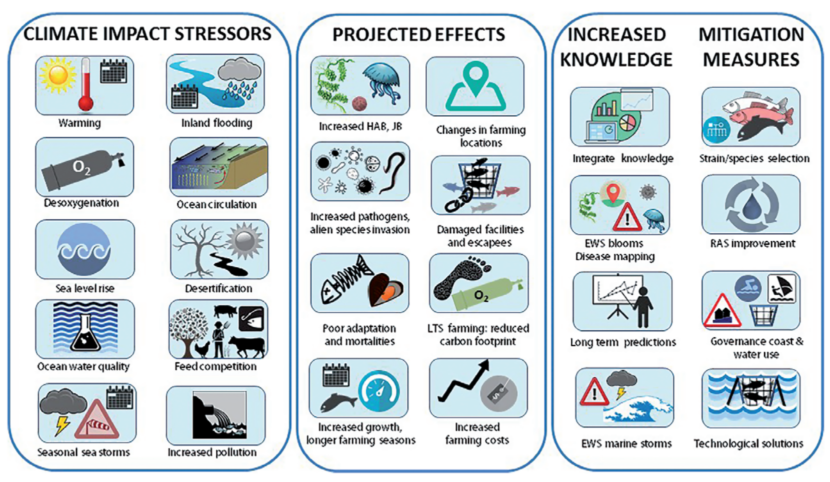
- Advancing our knowledge on: (i) the relationships between genome and epigenome and the tolerance to diseases and heat and water stresses, and (ii) the role of the gut microbiome in tolerance to heat stress and resistance to diseases.
- Assessing nutritional, reproductive and management strategies to mitigate the impact of climate change, in particular the effects of heat stress.
- Advancing in the knowledge of epidemiology of prevalent and emergent diseases and developing tools to diagnose, prevent and control. On-farm monitoring of animal behaviour and physiological parameters based on nanotechnology and new developed ITs tools will bring about early detection of ill animals. The development of vaccines and programs of vaccination is of primary importance to improve the capacity of prevention and control.

Adapting aquaculture systems: from anticipating the impacts to planning and optimizing management

Aquaculture systems are vulnerable to gradual change of climatic conditions and extreme weather events often resulting in severe loss of stock and infrastructure. Possible adaptation and coping measures require additional research into:

- Modelling towards early warning systems (EWS) of water temperature effects on aquatic pathogens and harmful biological blooms. Harmful algal blooms can lead to the loss of bivalve stocks, which have been estimated to cause losses globally of €200 million in one year and can also lead to illness in humans who consume effected shellfish. Jelly fish blooms have also been identified as a risk in the Mediterranean finfish farming due to oxygen depletion in sea cages and skin erosions (Bosch-Belmar et al., 2017). Fish and mollusc pathogens are also important economic drivers of aquaculture production. Thus, progress in the development of early detection systems of harmful blooms and aquatic pathogens, including the integration of diverse methodologies from image detection to on-site methods with light sensors and smart devices is imperative.
- Developing EWS of marine storms and development of technological solutions to avoid massive damage to marine infrastructures. Increased storminess (increases in wind velocity and changes in direction, water currents and waves) and increased frequency of extreme events (such as

FIGURE 2–Climate impact stressors affecting aquaculture activities, their projected effects and the needs to increase the knowledge that will make possible to implement mitigation measures



storms, floods, and droughts) are expected to have a negative impact on offshore mussel raft and fish cage aquaculture in the Atlantic and Mediterranean basins.

- Devising integrated spatial planning for aquaculture farm setting that consider governance strategies for the coastal use and preservation of water quality. Because of high risk of a reduction of aquaculture suitable areas and more stringent legal conditions for the establishment of new facilities we need of better site selection methods that balance resources conservation and production.
- Advancing in new technologies to reduce water use and increase biosecurity. Recirculation aquaculture systems (RAS) reduce water needs, improve the production and reduce the impact of pathogens in inland and marine cultures. RAS will allow the delocalization of fish farming from pristine waters, and will compensate the disappearance of inland open flow and coastal ones impacted by climate change.

3.3. Mitigating the impact and reducing emissions: negative emission options and low-carbon footprint primary production systems

The land-based mitigation pathway: Towards a carbon efficient use of the land

Global models predict that meeting the ambition goal of the Paris agreement of limiting warming to 1.5 °C above pre-industrial level will be only possible with negative emission. Among the negative emission technologies, land-based options are gaining the attention. Land based mitigation options include among others measures: (i) afforestation/reforestation; (ii) sustainable forest management (see section 3.4.1); (iii) biomass energy with carbon capture and exchange (BCSS); (iv) soil carbon sequestration (see section 3.3.2) and biochar application. It is estimated that land sector could deliver up to 15Gt CO_2 eq year-1 (about 30% of the mitigation) up to 2050 while contributing to several sustainable development goals (Roe et al., 2019). The feasibility and suitability of implementing large-scale land-based carbon dioxide removal technologies have been however questioned because of their water and footprint that would result in an increasing demand and competition for land and adverse impacts on biodiversity and food production.

Further research is needed on the affordability, reliability and sustainability of land-based mitigation pathways. This will address the following key issues: (i) incorporate environmental and social safeguard in integrated assessment models (IAM) of land-based mitigation pathways; (ii) evaluate how future climatic conditions could eventually affect the potential capacity of land-based mitigation option; and (iii) deploy integrated landscape planning to design and build carbon efficient landscapes. A carbon efficient landscape is that maintains or increases land–based carbon while delivering co-benefits such as for example enhancing biodiversity, soil fertility, halting desertification and land degradation, promoting water retention or diversifying livelihoods (Searchingeret al.,2018).

Enhancing soil carbon sequestration as a natural based solution for climate change mitigation

Protecting and rebuilding soil C is a powerful Natural Climate Solution to increase carbon sinks and deliver negative emissions. Soil C sequestration comprises up to 47% of the mitigation potential for the agricultural sector (Bossio et al., 2020), and delivers important ecosystem services in addition to climate mitigation such as soil fertility, water retention and pathogen control.

However, despite its great potential in agricultural systems, the practical implementation of climate mitigation strategies focused soil C lags behind its potential.

We have identified four research lines devoted to meet the key challenge of building soil C as a natural climate solution to mitigate the climate change contribution of agriculture and forestry. First, soil C sequestration may be promoted via multiple agricultural practices (improved residue management, reduced tillage, cover cropping, biochar), but their potential varies across climatic and soil conditions. Second, soil C is stored in a mixture of organic matter fractions (mineral-associated vs. particulate) that differ in their stability against microbial decomposition, determining the vulnerability of soil C stocks to climate warming and agricultural practices. Third, there is a trade-off between soil C storage and the emission of greenhouse gases with high warming potential, as agricultural practices increasing soil C sequestration can also enhance CH_4 and N_20 emissions. Finally, climate warming may stimulate the loss of soil C to the atmosphere, reinforcing climate change, and these losses may be fuelled or compensated with agricultural practices.

Generalizing soil C sequestration as a management goal in agricultural systems requires the design of monitoring programs at the farm level coupled with the increasingly more available remote sensing measurements. To do that, methods allowing a cost effective and straightforward quantification of soil C are needed

Deploying low carbon footprint aquaculture

All aquaculture systems should contribute to mitigate global change by optimizing every step of the cultivation process (from hatchery to harvest) to reduce their carbon footprint (net greenhouse gas emissions) and environmental impact (e.g. eutrophication, metal, organic and emerging pollutants). But further research is needed to foster the mitigation potential of aquaculture activities. Low Trophic Species (LTS) aquaculture (i.e. microalgae, macroalgae and bivalves) is a low carbon footprint activity with potential to sequester atmospheric CO_2 and, therefore, contribute to global warming mitigation. LTS aquaculture also contributes to the good environmental status of coastal ecosystems. Conversely, as LTS are fed by the environment, these aquaculture systems are more sensitive to climate and global change than high trophic species (HTS). Combining complementary cultures of LTS and HTS, as in the Integrated Multitrophic Aquaculture systems, also contributes to reduce the carbon footprint and environmental impact of HTS aquaculture activities. Eventual inclusion of LTS aquaculture in the international carbon trading market implies proposing algal biomass and bivalve shells applications that ensure the long-term preservation of the trapped CO_2.

3.4. Maintaining and enhancing carbon stocks and the provision of ecosystem services in threatened forests

Fostering adaptive forest management to climate change

Lack of forest management (in a gradient from non-intervention to intensive silviculture) to adapt forests ecosystems has resulted in high-density stands vulnerable to recurrent disturbances (e.g. pest and diseases outbreaks, wildfires, drought-induced dieback, and mortality). Forests need new planning tools and solutions to predict and forecast the influence of management practices on disturbance regimes and associated dynamics (Vilà-Cabrera,et al., 2018). Such tools must explicitly address the margin for manipulation, including among others the structure of the ecosystem, current and potential range of variation in stand composition, history of disturbance or disturbance suppression, and stand dynamics over time. Additionally, this conceptual advance must be accompanied using new technological tools (e.g. remote sensing, big data analysis, modelling, TIC, etc.) without which it is not guaranteed the future sustainability of forest ecosystems.

Items to be addressed to develop these tools are, among others:

- Identifying structural, ecophysiological or functional traits and related processes that are most sensitive to forests dynamics, in particular new stress conditions (e.g. global change, droughts, pest and diseases, pollution, etc.).
- Establishing traceable methods, based on eco-hydrological processes and mechanistic models, that explicitly relate forests ecosystem services (in particular water and C cycles) with forest management, paying special attention to the context of global change.
- Determining what are the management options applicable in the short and long term (e.g. when and where management adaptation strategies should be employed) to adapt Spanish forests to extreme climatic events as droughts and the analysis risks that intervention will make effective, given various ecological, economic or social scenarios.
- Integrating the objectives for managing forest at landscape scale to alleviate climate- related stresses and to enhance forest capacity to

resist, tolerate and adapt to a dynamic environment. Mosaic-liked landscapes that include agro-silvopastoral systems must be part of the forest management approach focused on resilience.

- Incorporating the current technological paradigm (e.g. remote sensing, wire-less sensors, IoT, etc.) into the silvicultural adaptive approaches/ strategies that can address a complex ecosystem-specific climate change adaptation treatment in a gradient from field to big data integration and decision support.

Coping with wildfires: Managing landscapes for generating ecologically and socially sustainable fire regimes

Wildfires are currently one of the most important sources of variability, heterogeneity, and dynamism in our landscapes. They alter plant and animal population occurrences (extinction) and sizes, modify community and landscape structure, affect biotic interactions and open opportunities for new species including invasive ones. Wildfires within the historical variability of the fire regime are an evolutionary pressure that may generating biodiversity (He et al. 2019) and ecosystem services; but abrupt changes in fire regime may be detrimental for biodiversity (Keeley and Pausas 2019). Thus, understanding how species and biotic interactions respond to wildfires (at ecological and evolutionary scales) is a key step for setting appropriate land management and conservation programs. Traditionally wildfires have been viewed as an external factor, a "forest problem". The research in the last decades suggest that wildfires needs to be viewed as an intrinsic factor to ecosystems and societies, so that once it is integrated in the system, we can better understand it and managed it. In order to enhance our understanding for a better management of wildfires, we need to know:

- What are the fire regime thresholds that generate abrupt changes in biodiversity?
- What is the adaptive capacity of the species to changes in fire regime?
- What are the ecological (biodiversity, biogeochemistry) consequences of fire regimes changes?
- What are the ecological consequences of managing landscapes for protecting people and infrastructures?
- What is the proportion of variability in species distribution and biodiversity explained by fire regime?

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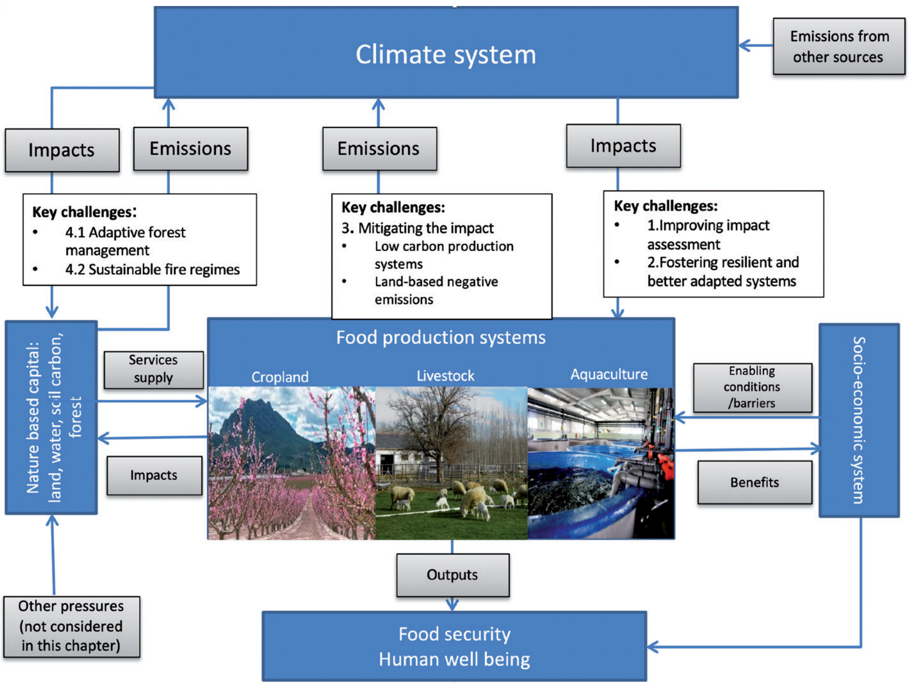
ACADEMIC SLIDE



CHALLENGE 6

ABSTRACT

Our unsustainable use of nature is bringing the Earth system and its capacity to recover from global changes beyond the environmental boundaries that supported us as a society. Here, we discuss some urgent challenges that should be addressed for the human species to live with undesirable products resulting from its development: sustainable use of nitrogen, watersheds management for preserving water resources and their quality, environmental impact of plastics, increase of the resilience of marine ecosystems, restoration of the deteriorated marine coastal ecosystems, or the early detection of emergence of diseases. We advocate for the use of Nature based solutions to mitigate environmental problems, and also consider subjective wellbeing issues in the governance of societies for a future healthy planet.

KEYWORDS

Sendai Framework | nitrogen cycling | watersheds management | plastisphere | bioengineering | resilience | marine ecosystem restoration | zoonotic diseases | natural capital | social capital

CHALLENGE 6

HEALTHY PLANET: HAZARDS, RISK MANAGEMENT AND SOLUTIONS-ORIENTED RESEARCH

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1. INTRODUCTION AND GENERAL DESCRIPTION

A 10,000 year-long period of stability of the earth system has provided the necessary conditions for agriculture to develop and for us, as a society, to thrive. This stability is now challenged by our unsustainable use of nature, exacerbated by the fossil fuels dependency of our steadily increasing energetic demands, with negative impacts of humans on both the Earth system and its capacity to recover from change. With a degraded resilience capacity, the future of Earth may go beyond the environmental boundaries that supported us as a society. It seems paradoxical that the same development that allowed us to thrive is now jeopardizing our future. The Sendai Framework for Disaster Risk Reduction 2015–2030 was one of three landmark agreements adopted by the United Nations in 2015, together with the Sustainable Development Goals of Agenda 2030 and the Paris Agreement on Climate Change. In May 2019, the UN Office for Disaster Risk Reduction (UNDRR) and the International Science Council (ISC) jointly established a technical working group to identify the full scope of hazards relevant to the Sendai Framework as a basis for countries to review and strengthen their risk reduction policies and operational risk management practices. The hazard list provided by the technical working group identified >300 hazards grouped in eight clusters: (i) meteorological and hydrological hazards, (ii) extraterrestrial hazards, (iii) geohazards, (iv) environmental hazards, (v) chemical hazards, (vi) biological hazards, (vii) technological hazards, and (viii) societal hazards. The way these hazards interact and the complex interactions between natural, social and technological systems, and how those interactions affect, across time and space, the planet's life support systems, socio- economic development and human wellbeing are fundamental issues that need to be properly addressed for global sustainability.

Hazard information when combined with exposure, vulnerability and capacity is fundamental to all aspects of disaster risk management, from multi-hazard risk assessments for prevention and mitigation to warnings and alerts, to disaster response and recovery, long-term planning and public awareness. A successful understanding of hazards for a healthy planet needs to move from managing disaster events to managing risks, by addressing the systemic drivers of risk in relation to climate change, health, sustainable development, and resilience building.

This chapter focuses on some challenging points combining natural and social sciences selected as snapshots of the complexity, multidisciplinarity, and potentials of the approach at CSIC.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Addressing the risks for human well-being that are associated with environmental degradation requires an extensive collaboration among contrasting scientific disciplines. Risks spread from climate change to pollution and from pandemics to the deployment of crucial resources such as fresh water. To anticipate these risks, to handle and correct them and to restore degraded ecosystems can only be achieved by multidisciplinary teams including biologists, physicists, modelers, medical scientists and veterinaries but also economists and a wide range of social scientists. This is in fact the spirit of the One Health program of the World Health Organization of the United Nations that CSIC is particularly well suited to tackle.

3. KEY CHALLENGING POINTS

3.1. Environmental Risk Management and Nature Based Solutions

Sustainable Nitrogen use

Nitrogen cycling through the biosphere rapidly doubled when abundant and cheap energy provided by the mobilization of oil reserves allowed the massive artificial fixation of nitrogen. A planetary boundary of still unknown consequences was crossed when humans became the stewardshipers of the nitrogen cycle. Reconciling high nitrogen demand for food supply with a safety biosphere became a primary challenge (Galloway et al 2008).

Shortly after the First World War, the Haber-Bosch chemical method for converting molecular nitrogen into ammonia was discovered. Roughly, the production of fertilizers accounts for 30% of all the nitrogen that circulates through the biosphere. The leguminous crops contribute another 15%, and 7% combustions in air; altogether more than half of the reactive nitrogen in the biosphere. Unfortunately, this acceleration of the nitrogen cycle leads to serious environmental problems because of the low use efficiency and the release of nitrogen contaminants to waters and atmosphere. Some of the early consequences, such as acid rain resulting from the emissions of sulphur and nitrogen oxides, were striking and corrective measures upon the main focus of pollution provided quick results. However, since then, little has changed because action on more diffuse and extensive sources is exceptionally complex. The global nitrogen scenery has changed little; for decades, estimates have been similar and hardly reducing uncertainty (Fowler et al. 2013).

Between 1900 and 2000, the application of methods of fertilization in agriculture (manure, commercial fertilizers and extension of the cultivation of legumes) increased > 100-fold. Nonetheless, the efficiency of use — understood as the nitrogen in harvest compared to the applied — decreased from > 60% to < 50%. This low yield results in increasing nitrate levels in waters and the emission of ammonia and nitrogen oxides into the atmosphere. Thus, pollution is transported far away from the fields. In hot spots of fertilizer use, the contribution of ammonium to total nitrogen deposition is increasing, becoming the majority form over large rural and remote areas. On the other hand, the metabolism of cities also returns large amounts of nitrogen to wastewater, generating a high treatment cost. There are health and environmental problems related to both scarcity and excess of nitrogen. Therefore, the balanced use of nitrogen is one of the main challenges for a sustainable society.

In present days, atmospheric transport and subsequent deposition have become the dominant nitrogen distribution process on a global basis, equivalent to about one-fourth of the total global nitrogen flux. The release of nitrous oxide (N_2O, a gas with 300-fold more greenhouse capacity than CO_2) is also a major concern. The amount of N_2O in the atmosphere has been increasing, with no signs of slowing down, over the past decades. It becomes essential to understand which factors control the $N_2O:N_2$ ratio. This question concerns wastewater treatment systems but also large areas of the planet affected by the atmospheric deposition of reactive nitrogen. Research based on molecular biology techniques, use of stable isotopes as tracers, and skills on simulating the complex nitrogen cycle may foster a required transition from heuristic knowledge to knowledge based on process understanding. Sustainable use of nitrogen by society necessarily implies increasing scientific knowledge to efficiently manage the nitrogen processes in which the natural and the human cycle are inevitably intertwined.

Integrated watersheds management

Diffuse and point source pollution in human-impacted watersheds has been increasing over decades. Simultaneously, the acceleration of the hydrological cycle is leading to an increase in the frequency of floods and droughts. The interaction between watershed pollution and climate variability can have devastating consequences for ecological and societal systems, and compromises the availability of freshwater resources in the future (Kaushal et al., 2018). The challenge is especially difficult in Mediterranean regions, where water is scarce and the management of freshwater resources is critical.

Water quality has been a priority for the European Union for many years. In 2000, the Water Framework Directive envisioned a good status of all EU waters by 2015. This aim was accomplished only by half of EU water bodies in 2012. Since then, water quality has improved, but only slightly. The 22% of EU water bodies still suffer of diffuse and point source pollution, while nutrient excesses precludes a good status of waters in about 30% of water bodies. Restoration and mitigation actions are complex and expensive. In most cases, interventions are conducted at individual sites, and they are focused on resolving either diffusive or point source pollution, one contaminant at a time. This strategy has appeared to be insufficient, and leads only to small improvements on the overall water quality. Managing water pollution needs to move beyond individual chemicals and individual sources. Evidence is growing that biogeochemical cycles of essential elements such as carbon and nitrogen are strongly linked to each other, and that human impacts lead to the formation of 'chemical cocktails', this is, groups of pollutants with similar fate and transport pathways that can originate from multiple sources (Kaushal et al. 2018).

Watersheds and their associated drainage networks are fundamental landscape units. Freshwater resources and water quality are ultimately determined by the combination of natural and anthropogenic processes that influence storage, transport, and transformation of solutes through the drainage area. Analogously to the different organs of a living organism, the impact of different land uses and human activities within a watershed cannot be dissociated from each other. They need to be taken as whole in a holistic manner if we are to understand water quality signatures and warrant freshwater resources. Watersheds can be seen as sieves and filters of particulate and dissolved organic matter, mineral solids and colloids, many times bounded to organometallic complexes and other organic contaminants. Watersheds can be also seen as chromatographic columns capable of eluting ions from soils and sediment exchanges sites. Finally, watersheds are powerful bioreactors capable of transforming solutes such as carbon, ammonium, nitrate, phosphate, and sulfate. Thus, watersheds can act as important control points of point source and diffuse pollution when environmental conditions favor biogeochemical reactivity. The formation, storage, and transport of these different families of 'chemical cocktails' through soils, groundwater, and sediments depend on the size and density of particles, the location of watershed sources, the frequency and characteristics of storm events and hydrological connectivity, and in the case of bioreactive solutes, on the redox conditions and biological demand within the watershed and along the drainage network.

Cities and urban areas keep growing, and so do water demand and wastewater production. While waste water treatment plants are essential for keeping freshwaters within reasonable limits of healthiness, point source effluent inputs strongly impact stream water quality and functioning. This is especially noticeable when mean discharges are low and streams have a low dilution capacity. Decades of channel engineering and 'dammification' have ensured water and energy supply, but at the same time, have altered natural flow regimes and hydrological connectivity, decreasing the hydrological resilience of fluvial networks, floodplain productivity and altering sediment dynamics in deltas and coastal areas (Nilson et al., 2005). In agricultural watersheds, the application of artificial fertilizers and pesticides has led to unprecedented levels of nutrient excesses and contaminants in groundwater and superficial waters.

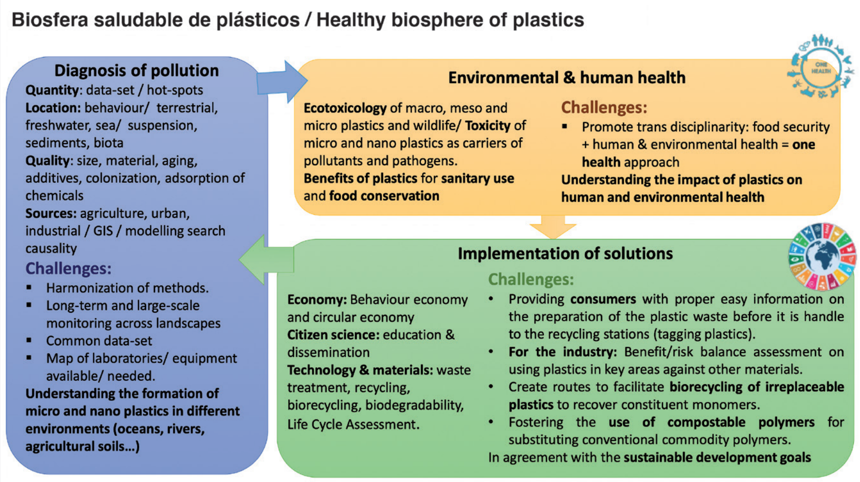
This type of diffuse pollution is extremely difficult to revert. Humanity is now starting to foreseen the long-lasting effects of these impacts on freshwater resources.

Given that watersheds are highly heterogeneous landscapes and that many different actions can be taken to protect water resources and reduce water pollution, it is crucial to carefully plan integrated management strategies that maximize benefits while reducing socioeconomic costs. The implementation and maintenance of long-term monitoring programs of surface and subsurface waters from headwaters to lowlands is fundamental. High-temporal resolution sensors are becoming increasingly affordable and widespread in national monitoring worldwide. Hydrological and physicochemical variables that can be used as proxies of water quality such as dissolved oxygen, temperature, turbidity, and electrical conductivity should be prioritized. A systematic monitoring program based on scientific criteria is perhaps the most important action that can be taken by public administrations, and without no doubt, the wisest investment at the long term. The reduction of impervious covers and the use of green infrastructures such as green roofs and permeable pavements can help to increase the transport of sediments and solutes while reducing nutrient loads in urban areas. Managing water diffuse pollution by protecting and restoring riparian buffers and wetlands is also key. Natural and engineered wetlands can contribute to reduce nutrient loads, but also remediate contaminants, pharmaceuticals, and metals. Moreover, plants in riparian zones contribute to reduce soil erosion and preserve natural flooding areas, which increases hydrological resilience during extreme hydrological events.

Management of the environmental impact of plastics

Plastics have become essential to our societies in less than a century, especially because they combine low cost and excellent functional and structural properties. Citizens from developed countries are increasingly worried about the impact on their health and on the environment of every day products made of plastics. Current investigations reveal that plastic pollution is not only widespread in the oceans, but also in the atmosphere, and in terrestrial and freshwater ecosystems. Most plastics constitute highly recalcitrant pollutants and act as long-lasting reactive surfaces, containing additives and/or absorbing organic matter and toxic substances. However, the complex nature of plastic pollution, including a large set of compounds, forms and sizes is poorly understood, with a lack of standardized analytical methods. Additionally,

FIGURE 1—Workflow for dealing with plastics: from diagnosis till solutions



plastics themselves form specific niches for microbial life what has been defined as "The Plastisphere". Understanding of the sources, fate, transformations, occurrence and impact of plastics (from macro- to micro- and nano-plastics) remains very limited, particularly in terrestrial and freshwater environments.

The huge unintended impact of plastics in the environment is a crucial challenge of linear plastics economy. There is a need to understand the benefits of plastic but we have to balance them against its health and environmental costs. It is a complex issue that demands interlinked research covering a large variety of environmental, social-political, educational and economic challenges in line with the one health and the sustainable development goals approaches (Figure 1). In this context, the European Commission has fostered the circular economy policy, that applied directly to plastics. Single used plasticsare to be minimized and, for example, there is a European mandate to ban the popular single use plastic cutlery, plates and strokes. Educating citizens in responsible behaviors related to plastic used would help to take profit of using plastic materials while minimizing the environmental threats. New generations are more and more conscious on the problem of plastic waste. Challenges in educating the society on this issue should cover citizens and industry. Initiatives to inform the citizenship are, for example, providing consumers with easy information on how to prepare plastic waste at home before it is handled to recycling stations (tagging plastics) to boost circular economy. This education of the citizenship would demand on industries to become more efficient in the use of plastic specially on packaging.

Another fundamental issue is related to the carbon footprint of using alternatives to carbon, that in some cases is extremely higher than that of plastics. The alternatives are related to the way we use plastics, and basically centering efforts in reducing, reusing and recycling existing plastics. From a scientific point of view, challenges include the seek for alternative materials that could not threat nature, either in the form of waste or in the form of carbon footprint. Also, understanding the formation of microplastics (for example in oxo-degradable polymers) to recover them and exploiting the possibility of reusing them in the manufacturing of recycled plastic materials. And finally, promote the understanding and application of biorecycling through bacteria that may allow the recover the constituent monomers of the plastic materials.

Bioengineering and Nature Based Solutions

Evidence is growing that small ponds, temporary wetlands, or even wetlands geographically disconnected from the fluvial network contribute to decrease loads of nutrients and other contaminants at the landscape scale. In the case of nitrogen, for instance, substantial load reductions (up to 40%) can be achieved if wetlands occupy areas as small as 5% of the total drainage area (Verhoeven et al., 2006). The construction of reactive vertical barriers and horizontal beds filled with materials such as organic matter can help to remove groundwater metals and nitrate via denitrification, an action especially important in those places with chronic groundwater pollution. The protection of natural flow regimes, flow spatial heterogeneity and stream-floodplain connectivity is essential, from headwaters to lowlands, and facilitates retention of water, solutes, sediments, and particulate organic matter, and resilience to disturbance (Palmer and Ruhí, 2019). Headwaters are especially important because these areas drain up to 70% of the watershed, and thus the benefits of protecting headwaters on water storage and quality, cascade down through the whole fluvial network. Finally, stream restoration activities such as channel reshaping, wood addition, or enhancement of natural flow regimes can help to manage sediment transport and nutrient transformation along particular sections. In addition, towns and cities must take a step forward with an absolute change of criteria in relation of the management of the environment. Creating modern urban areas means, among other things, improving the quality of life by improving the quality of the urban environment. Towns and cities must restore green areas and manage some of their problems within their own urban area. These are essentially Nature Based Solutions (NBS), so the design of these green areas with tools like Soil& Water bioengineering should have specific objectives added to landscape improvement. A few examples follow.

Stormwater management and improvement. The management of urban runoff has been characterized as primarily a hydrodynamic phenomenon related to high levels of waterproofing and rainfall patterns, in this sense, urban runoff will be managed, both in Mediterranean regions because of his regime torrential rainfall intensity and in continental areas for its periodicity. It was not until recently that it has become clear that the management and treatment of pollutants present in runoff load is a critical control point that should also be contemplated. Green areas should act like rain gardens, improving aquifer recharge, reducing runoff and making flooding less intense. These areas should be especially active at improving the quality of the first flow.

Improving air quality and controlling wind and temperature. Similar NBS criteria can be applied for air improvement and oxygen production, temperature and wind control, and CO_2 retention in towns. The future gardens, parks, roundabouts and roadsides should be functional ecosystems. We should give architects and engineers clear tools for the new cities. Smart cities are made with NBS.

Biodiversity criteria in the design of structural protection systems. In urban rivers, in road slopes, in drainage, etc., engineering solutions have been created to achieve security. In the XX century these spaces have been solved using concrete, stones, and similar hard materials. Nowadays, bioengineering solutions are introduced to gain in landscape quality and resilience against natural impacts. NBS, in addition to consider the mechanic stability, have positive influences on the environment such as introduction of biodiversity, capacity of biodepuration of water and air, friendly landscape, among others, providing additional ecosystems services.

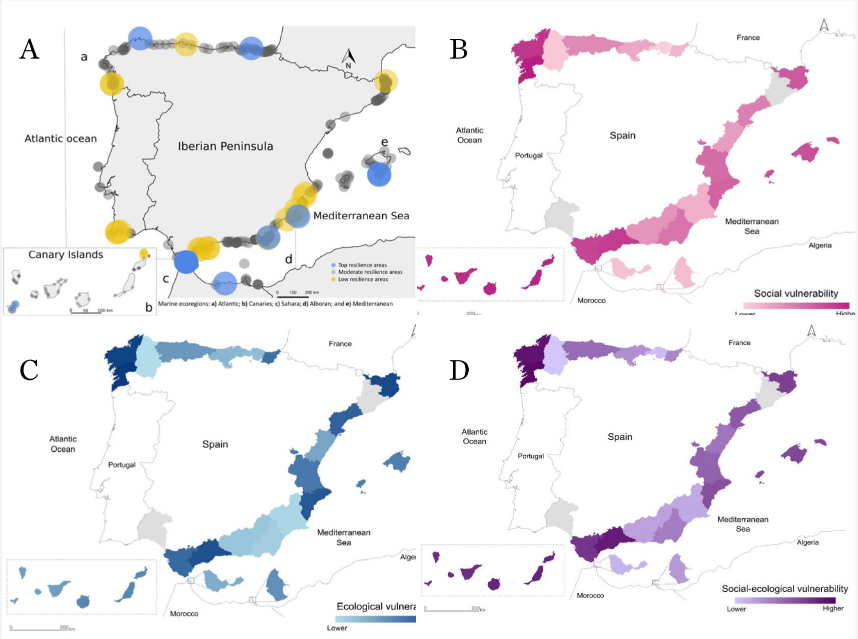
River improvement to reduce diffuse pollution from WWTP effluents. Southern Europe rivers are very vulnerable to human pressure since they usually have low flows or are even dry during certain periods of the year, and therefore their ecological quality depends on the contribution regime of effluents from wastewater treatment plants (WWTPs). Due to this low flow, they have a low capacity to dilute the contributions, mainly nutrients, emerging pollutants and pathogens. This fact means that, although the WWTPs legally comply with the parameters set by the states and the European regulations on the quality of the effluents, the low dilution capacity in Iberian rivers for example, leads to overwhelming pressure on their biodiversity and functional capacity, and their optimal purification implies a high economic cost. The present and future climate change scenarios exacerbate these effects. NBS can substantially improve the river habitats by adapting the riverbed, the banks and the effluent path of the WWTP. Bioengineering based in autochthonous plants increase rivers bioreactivity and a large potential exist in this research field. Further investigations will certainly solve these problems in a cost- effectiveness way.

Sustainability and resilience in marine ecosystems

The global environmental crisis is now rooted in a society that demands profound changes to reach sustainability. A decade ago, the Convention on Biological Diversity specifically addressed the need to enhance resilience (Aichi Biodiversity Target 15). Seven years later, the International Union for the Conservation of Nature established the Resilience Thematic Group to clarify the concept of resilience and to demonstrate the value of tools for resilience-based natural resource stewardship, disaster risk reduction, and ecosystem- based adaptation. The truth is painful. A decade after the establishment of the Aichi Biodiversity Target 15, data on resilience remains elusive and our empirical understanding of resilience is still in its infancy. As a complex concept, quantifying resilience is a challenge that needs the integration of numerous biological, environmental, and anthropogenic factors (Maynard et al, 2010). In tropical marine regions, the resilience assessment framework established an approach to calculate a site-specific resilience indicator with strong management implications (Maynard et al, 2010). This approach has been adapted and used to assess resilience in several tropical locations and it could be instrumental in gaining knowledge about the resilience of the oceans. For a better environmental management, accurate but simplified resilience indicators are needed that provide baseline resilience data to help track natural patterns of resilience and, also, the consequences that human actions have on the resilience of the oceans.

Multiple biological, environmental, and anthropogenic factors are known to regulate the resilience of temperate marine systems. The need for data is large

FIGURE 2–Rocky reefs in Spain (A) with high (blue) and low (yellow) resilience values as measured by the IRIS. Social (B), Ecological (C), and Social-ecological (D) vulnerability of the Spanish provinces to tourism and fishing (unpublished data by JA Sanabria&N Lazzari)



and could benefit from validated protocols of citizen science (e.g., the Reef Life Survey program www.reeflifesurvey.com) to gather biological data. In turn, massive environmental data can be obtained from publicly available repositories (e.g., Bio-Oracle marine layer dataset www.bio-oracle.org). Finally, anthropogenic data can be obtained from multiple sources supported by social scientists. Overall, high-quality data provide a huge array of possibilities to advance science and to inform policy-makers (Sanabria-Fernández et al. 2019). Objective resilience values can be generated and areas that would benefit the most from specific management actions, such as regulation of fishing activities can be identified. In a recent study carried out in Spain, over 5% of the rocky reefs investigated had low resilience values, suggesting that their capacity to recover from disturbance is at risk (Figure 2). The resilience of some of these sites could be increased by over 20% through adequate management actions. Overall, pollution management would provide the largest benefit to the resilience of the Spanish rocky reefs, with regulation of diving and fishing activities in second and third positions (Figure 2).

Restoration of marine habitats

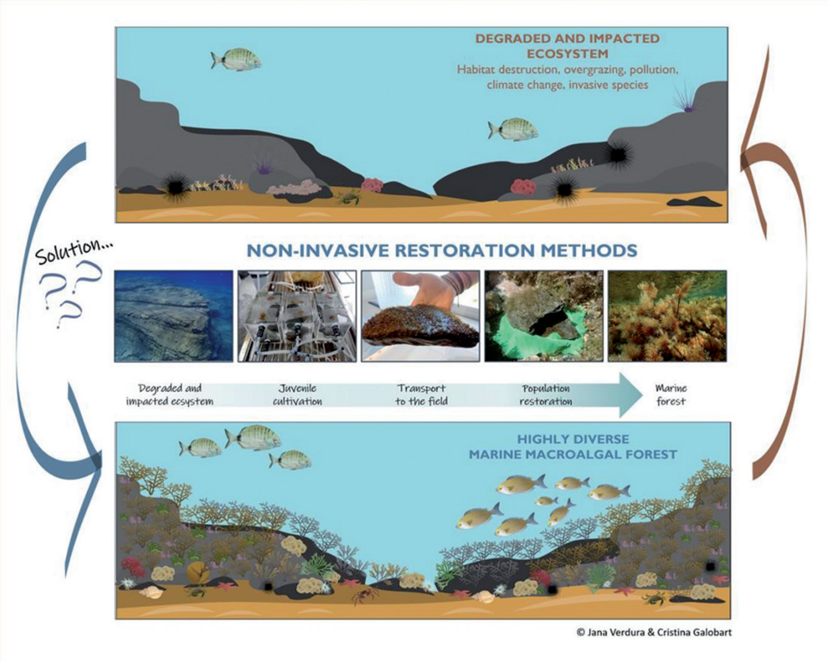
Marine coastal ecosystems are among the most impacted systems by human stressors (Bevilacqua et al., 2020), and ensuring the provision of essential ecosystem services requires not only the protection of native habitats but also effective restoration through new approaches (Brancalion et al. 2019). The final goal for restoration and conservation is to shift from the traditional, narrow, species-focused plans to broader approaches incorporating seascape-scale perspectives to achieve multiple objectives, including reducing species extinctions, mitigating injurious climate change and promoting sustainable livelihoods (Figure 3). There is widespread agreement that monitoring is fundamental for successful restoration (Guariguata and Evans, 2019), but it needs to be reframed and include different habitat types to provide integrated knowledge of ecosystem functioning and ecosystem services. Then, conservation and restoration actions should embrace habitat variability and support adaptation to local circumstances to increase ecological resilience in a rapidly changing world. Among biological and ecological features, life-history traits, population connectivity, spatial distribution, structural complexity, and the potential for regime shifts are identified and scored as the main biotic factors contributing to the successful accomplishment of habitat restoration (Bekkby et al. 2020). However, at present most of these features still remain unknown for many assemblages and species.

Viability of ecological restoration could be strongly compromised by accelerated environmental modifications associated with climate change. A promising, but as yet untapped, opportunity for enhancing the climate-resilience of restoration investments rests in the exploitation of natural genetic variability of key species (Prober et al. 2015). While the capacity of plants to adapt to environmental change through plasticity, selection, or gene flow has been intensively explored (Prober et al. 2015), for marine habitats and species the available knowledge is scarce or null. In addition, the impacts of climate change are highly variable geographically, and a place-based understanding of climate change threats to marine ecosystems is needed. Combined modeling approaches considering intrinsic adaptation of habitats and species together with predictions of climate change trends and impacts, are essential to properly assess the fate that species, habitats and sites will follow when restored.

Emerging diseases: zoonoses and arboviruses

Zoonotic diseases are infections that humans catch from other animals. They can be caused by viruses, bacteria, parasites and fungi. Some examples of

FIGURE 3–Steps for integrated actions to restore deteriorated marine coastal habitats



zoonotic disease are: Anthrax, Ebola, avian influenza, rabies, Zika, and a number of coronavirus diseases, including SARS, MERS, and probably Covid-19 (Ahmad et al. 2020). Vertebrates hosting pathogens that can spillover to humans include bats, cats, birds, pigs, camels or horses. For some zoonotic diseases, non-human animals serve primarily as vectors, meaning that they transmit the disease between humans more than serving as host reservoirs. A special case of vector-borne diseases of current concern in Europe involve viruses transmitted by arthropods (e.g. certain species of ticks and mosquitoes), the so- called arboviruses. Diseases caused by mosquito-borne viruses, such as dengue, Zika, chikungunya, West Nile fever, Usutu, and yellow fever, are emerging and reemerging globally. The causes are "multifactorial and include global trade, international travel, urbanization, water storage practices, lack of resources for intervention, and an inadequate evidence base for the public health impact of mosquito control tools" (Roiz et al. 2018). In other cases, zoonotic diseases are transmitted among humans without requiring a vector, often transmitted by air, as is the case of infectious diseases originated by coronaviruses.

The emergence of zoonotic diseases is being shaped and intensified in complex ways by a variety of factors associated with global change, including biodiversity loss, environmental degradation, land use changes, and climate change (Franklinos et al. 2019). For example, there is mounting evidence that increased virus spillover events from animals to humans can be associated with biodiversity loss and environmental degradation, as humans further encroach on wildlands to engage in agriculture, hunting and resource extraction they become exposed to pathogens which normally would remain in these areas (Christine et al. 2020). Such spillover events have been tripling every decade since 1980 (Shield et al. 2020). Another study concludes that the anthropogenic destruction of ecosystems for the purpose of expanding agriculture and human settlements reduces biodiversity and allows for smaller animals such as bats and rats, who are more adaptable to human pressures and also carry the most zoonotic diseases, to proliferate. This in turn can result in more pandemics (Gibb et al. 2020). Both air-borne and vector-borne emerging zoonotic diseases are currently challenging the existing global health infrastructure and organization.

The digital revolution coupled with data science, and the use of breakthrough multi- analytical data sources and technologies (e.g. social networks, global databases, active smartphone data collection) offers opportunities for infectious disease detection and management. Rapid identification and scalable management are essential to reduce the impact and costs of outbreaks. As a major part of emerging infectious diseases come from animals, a true shift in ability to detect would come from a deep understanding of the factors governing their emergence, focusing on the complex interplay of environmental and human factors that drive disease dynamics, and using those insights to develop scalable and actionable early warning systems. Future epidemiological research needs to combine and model data from a wide range of sources that reflect and track changes in drivers of (re)emergence and transmission of infectious diseases at almost real-time. Open and participatory science approaches together with novel technologies such as the internet of things (IoT) and smartphones, are essential to generate actionable connections between public health management, science, and citizenship, providing scalable and flexible data on vectors and infectious diseases that can be used together with traditional surveillance and management tools (Shepard et al. 2016).

Novel observational and computational laboratories should be designed to be used in 'interepidemic' mode' (i.e. in the absence of actual threats) as well as of immediate use in actual outbreak events (i.e. outbreak response mode). They may be able to reveal critical changes in the drivers of disease, (re)emergence and spread at a much earlier phase of an outbreak curve (when is the risk increased?), predict hot-spots for (re)emergence and spread of known and novel pathogens (where should we investigate?), and assess potential public health or animal health risks (how do we interpret and detect risk?). Technological innovation in public health including contact tracing and social distancing measures also raises however various challenges from multiple perspectives. Policymakers and public health managers aim to predict and control outbreaks faster with novel technologies, but often public health systems are not ready to accept innovative tools that require prior investment in IoT architecture and human resources. In addition, technology-focused responses often reinforce existing power structures and patterns of inequality, while at the same time masking the political considerations that underlie decision-making processes. As a consequence, an ethical, legal and societal perspective is required to solve tensions and risks of the use of novel technologies and big data approaches in the public health context.

3.2. Preserving human wellbeing and promoting good governance practices

Environment & Subjective Well-Being

The subjective wellbeing literature has empirically shown that the natural capital and the quality of the environment is essential to individuals wellbeing. Individuals are not necessarily happier living in high income countries, but rather if they live in cohesive societies with a sustained and stable economic development, with less poverty and inequality, and higher levels of employment and respect for the environment. Individuals subjective wellbeing depends not only on their objective personal situation (such as, their health, job conditions, and income), but also on their personality as well as on their surroundings (such as regional inequality and unemployment rate, environmental quality, and institutions and social capital in their region). Current evidence shows unequivocally that satisfaction with life depends, among others, on the quality of the environment. The natural capital and the overall environmental quality and the level of nature conservation is not only the base for sustaining life on earth and our economy, but it is also key for our health and wellbeing. It is crucial for policy making to understand the determinants of reported wellbeing not only to design policies that are welfare improving, but also to take into account individuals' reactions to policies.

With the increasing urbanization all around the world, there is an increasing number of individuals that live in urban environments, with high levels of pollution and lack of green and natural spaces. Pollution decreases life quality through health deterioration, lower productivity, and worse educational performance, but also decreases life satisfaction (van Praag and Baarsma, 2005). Nature becomes crucial in cities. Being close to natural or green areas within the city is correlated with both better physical and mental performance (individuals close to natural areas have a better social life and are more physically active) and higher life satisfaction (e.g., White et al., 2013). It has already been shown that hospitalized patients who were in rooms with views to a green space recovered earlier and stayed shorter days in hospital (Ulrich 1984). MacKerron and Mourato (2013) found that individuals were substantially happier in green spaces or natural areas compared to when they were in an urban environment. White et al. (2013) found that people were reported to have higher levels of wellbeing if living in cities with larger green areas. Thus, the increasing urbanization puts physical and mental health at risk and needs of proper risk management policies and actions.

Climate change and environment deterioration also affects individual wellbeing indirectly through anxiety about future uncertainty. This is known as eco-anxiety, a term accepted by the American Psychological Association since 2017. This term refers to the anxiety caused by the environmental problems, notably climate change and loss of diversity, and the risk that this has for future generations. Social reports show that a large percentage of the population sees climate change as an important threat. In 2016 the European Social Survey (ESS) reported that 74% of all respondents from the 23 countries were worried about climate change, but only 33% of the ESS respondents were in favor of increasing taxes to fossil fuels in order to reduce climate change. This survey revealed a need for enhancing scientific communication and social discussion on climate change threats and the best measures, actions and practices that should be committed for sustainability and human well-being.

Environmental change, risk, trust and governance

Since the end of the 20th century, our era has been characterized as a "risk society" (Beck 2011). The concept of risk is truly polysemic and is used both to refer generically to an undesirable event and to its causes, its probability or its expected statistical value. The terms dangers and threats have been used interchangeably to refer to these new anthropogenic risks that are beyond a probabilistic determination and which, linked to human action, can acquire a catastrophic and global character. For this reason, the term "danger society" is more appropriate to refer to our time. The uncertainty about facts, disputed values, enormous challenges (systemic risks) and urgent decisions, altogether calls for ethical debate, public deliberation, transparency and policies (social control with participation of non-experts in deliberation and decision). In other words, it calls for "good governance".

At a time of great uncertainties and risks, with global pandemics, economic crisis, mistrust, suspicion and fear of the future refer, a "special fear" arises as the fear that the society in which we live will collapse, the sensation of sinking and a feeling of loss of identity (Marina 2006). The antidote to fear is trust. Trust accumulates as a kind of capital that offers more opportunities for further action. In this sense, trust is a key element of the concept of "social capital", widely used in economics and social sciences, and which can be defined as the connections between individuals and social networks and the norms of reciprocity and trust that arise in this interaction. Social capital consists of the stock of active connections among people: the trust, mutual understanding, and shared values and behaviors that bind the members of human networks and communities and make cooperative action possible.

Mistrust and discredit are lethal for organizations, companies and institutions and undermine the basis of the political organization of society. Several OECD reports have identified a decline in the legitimacy of governments and a fall in confidence in public institutions in many countries since the 1990s, with a negative effect on the legitimacy of such governments and institutions. We therefore urgently need a "good governance" of risks and uncertainties. Governance basically means the management of public affairs and is characterized by a multi-centered type of decision-making, structured in complex networks through which relations between relatively autonomous but at the same time highly interdependent actors are organized. The idea of governance connects with a vision of democracy that is more open, more direct and more interactive as opposed to a closed, hierarchical and unidirectional practice. The concept of governance promotes co- responsibility and designates rules, processes and behaviors that influence the exercise of power. Five principles characterize "good governance" (which is what generates citizens' confidence in the institutions and the political system): openness, participation, responsibility, effectiveness and coherence (European Governance. White Paper 2001, https://ec.europa.eu/commission/presscorner/detail/en/DOC_01_10).

In short, governance aims at a form of coordination between political and social actors characterized by regulation, cooperation and horizontality. Governance is based on the principle that the solution of social problems is not carried out exclusively through a supreme authority but through the joint action of different actors and organizations. And it requires the administration and politics to recover a strategic capacity to be able to face the future challenges of society and its democratic configuration. There is an inability to anticipate the future that is of a structural nature. Only if politics recover strategic capacity will it succeed in moving from the world of repairs to that of configurations (Innerarity 2011), especially in the current context of major environmental and social changes.

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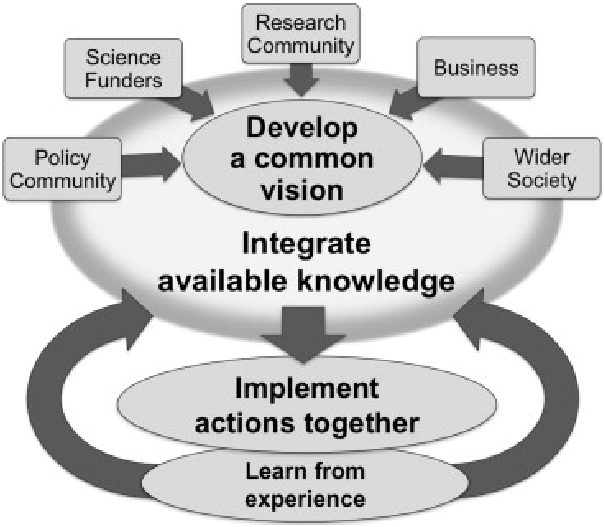
ACADEMIC SLIDE



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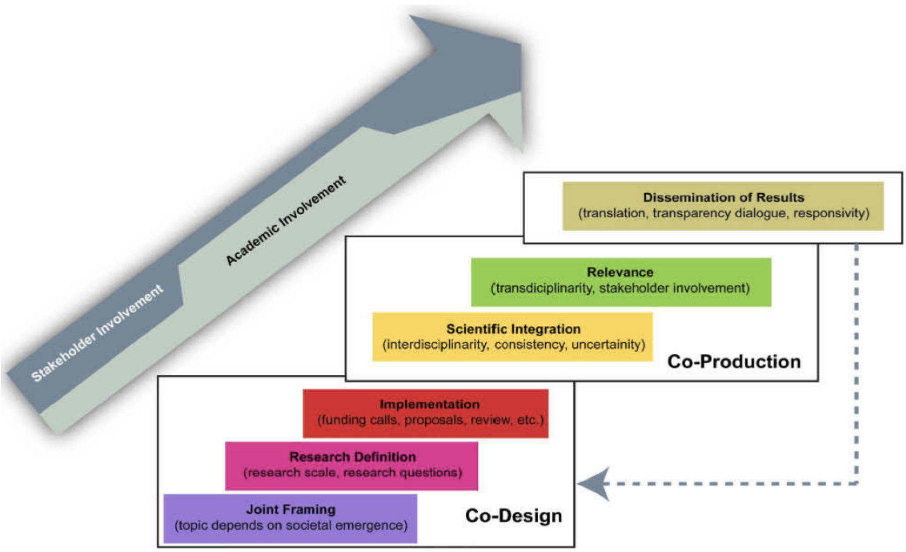
DISSEMINATION SLIDE



The environmental sustainability of the Earth system is at risk, and so do human welfare because of our dependency on it. Here we present challenges dealing with the understanding of how drivers of global change work, and how to minimize their effects on natural and human managed systems, with the aid of new concepts and edge-cutting technology. Their achievement should allow us to detect, understand, forecast and mitigate global change impacts related to climate change, the biodiversity crisis, polar regions, and managed ecosystems, and to improve the health of our planet in the coming decades.

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