RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

INRAE

International Science Foresight Workshop: Global Challenges and Research Gaps

The Royaumont process

REPORT February 2021

Table of contents

Please use the following reference to quote the report:

Soussana, J.-F., Weill, C., Caron, P., Chotte, J. L., Joly, P.-B., Aggarwal, P., ... Whitmee, S. (2021).
International Science Foresight Workshop: Global Challenges and Research Gaps.
The Royaumont process: INRAE (France), 25 p, DOI:10.15454/m3k7-j656

Foreword

Reaching the Sustainable Development Goals (SDGs), approved in New York in 2015, by 2030 in the most appropriate, inclusive and equitable way, calls for deep transformations in our societies. In particular, this will require addressing a number of intertwinned challenges concerning food, climate change, biodiversity, health, inequality and poverty and to enable transformative changes across multiple interconnected systems (land, water, health, food, environmental, and socio-economic systems).

In the decade 2020-2030, it is expected that researchers, in partnership with stakeholders, policymakers and actors on the ground, will not only provide knowledge to better understand major environmental and societal issues and their implications, but also provide options to engage in deep and necessarily innovative transformations towards sustainability.

Despite ongoing efforts, in particular in the Global Sustainable Development Report (GSDR 2019), we lack a science process to deliver integrated understanding on SDGs as a nexus. Furthermore, delivering integrative and actionable knowledge (Arnott et al., 2020) to meet Agenda 2030 raises many questions: how to re-legitimate scientific knowledge and preserve scientific integrity and ethics; avoid silos; coproduce knowledge with users, and promote iterative processes to deliver knowledge addressing the diversity of contexts, uncertainties and complexity? Would this require changes in institutions, in international research cooperation and in science-policy dialogue?

To answer these important and ambitious questions, high-level international experts have been invited in April 2020 by INRAE to participate in a workshop at Royaumont Abbey near Paris, France. In the context of the COVID-19 pandemic, the workshop initially planned in April, has been postponed until September. Meanwhile, a draft position paper has been circulated among the group of experts and three online sessions have been organized on 19 June, 23 June and 9 July to address the following questions and topics respectively:

1. **What have we learned from international expert assessments and foresight studies on grand challenges? How could assessments be improved in the future?**
2. **Emerging approaches for research and knowledge for transformative change, advances, gaps and challenges**
3. **Defragmenting scientific landscapes and science policy arenas through international co-operation to revisit and strengthen local to global connections.**

Between April and September, the expert group was asked to review a zero order draft of a paper proposed by the Scientific Committee. A first order and a second order draft, edited by the Scientific Committee were subjected to further revisions by the expert group. Following the online and presential presentations and discussions during the Royaumont workshop (September 9-11, 2020), it was decided that the third version of this paper, although too long for publication in a multidisciplinary journal, could be published as a report including recommendations endorsed by the Scientific Committee. A shorter version will be edited and submitted for publication.

We wish you a pleasant reading of this report of the Royaumont International Science Foresight Workshop on Global Challenges and Research Gaps!

The Scientific Committee

Group of experts

Names of Scientific Committee members are underlined

Dr. Pramod AGGARWAL, CIMMYT, CGIAR

Dr. Monique AXELOS, INRAE

Prof. Dr ir Imke DE BOER, Wageningen-University & Research

Dr. Thierry CAQUET, INRAE

Dr. Carole CARANTA, INRAE

<u>Dr. Patrick CARON</u>, University of Montpellier

<u>Dr. Philippe CHEMINEAU</u>, INRAE

Dr. Christine CHERBUT, INRAE

<u>Dr. Jean-Luc CHOTTE</u>, IRD

Dr. Mathieu DENIS, International Science Council

Prof. Jessica FANZO, John's Hopkins Berman Institute of Bioethics

<u>Dr. Patrick FLAMMARION</u>, INRAE

Dr. Jean-François GUÉGAN, INRAE/IRD

Dr. Christophe GOUEL, INRAE

Ségolène HALLEY DES FONTAINES, INRAE

Dr. Olivier HAMANT, INRAE

Prof. David HANNAH, University of Birmingham

Dr. Marion HETHERINGTON, University of Leeds

Dr. Christian HUYGHE, INRAE

<u>Dr. Pierre-Benoît JOLY</u>, INRAE

Dr. Cyril KAO, INRAE

<u>Dr. Antoine KREMER</u>, INRAE

Prof. Peter LANGRIDGE, The Wheat Initiative and University of Adelaide

Prof. Paul LEADLEY, University Paris-Saclay

Dr. Michael LEE, Rothamsted Research

Dr. Marcus LINDNER, European Forest Institute

Dr. Allison LOCONTO, INRAE

Dr. Mauricio Antonio LOPES, Brazilian Agricultural Research Corporation, EMBRAPA

Dr. Valérie MASSON-DELMOTTE, IPCC WG I, Co-Chair, University Paris-Saclay

Dr. Alan MATTHEWS, Trinity College

Raoul MILLE, INRAE

Prof. Robert J. NAIMAN, University of Washington

Prof. Elio RIBOLI, Imperial College London

Prof. Johan SCHOT, Utrecht University

Dr. Youba SOKONA, IPCC Vice-Chair

<u>Dr. Jean-François SOUSSANA</u>, INRAE

Dr. Andrew STIRLING, University of Sussex

<u>Prof. Daniel TOMÉ</u>, INRAE

Dr. Maria-Concetta TOMEI, Italian National Research Council

<u>Dr. Sébastien TREYER</u>, IDDRI

Dr. Saskia VISSER, Wageningen-University & Research

<u>Dr. Claire WEILL</u>, INRAE

Prof. Jacques WERY, ICARDA, CGIAR

Dr. Sarah WHITMEE, Oxford University

Recommendations

Inform Agenda 2030, transitions and transformations

In the decade 2020-2030, it is expected that research will not only provide knowledge, but will contribute to reach the Sustainable Development Goals (SDGs) in the most appropriate, inclusive and efficient manner.

In this perspective, scientists and scientific communities have to imagine and provide a landscape of scenarios and options for the future to engage in deep and much needed innovative transformations towards sustainability. For that purpose, they have to address grand challenges – climate change, biodiversity loss, land degradation, food security, health, poverty and inequality - in a synergistic way, and to study transition and transformation pathways towards sustainability at a range of nested scales, from local to global.

These goals imply to better qualify and quantify sustainability by studying, for a comprehensive set of SDGs, synergies and trade-offs across integrative options of sustainable land management, on the one hand, and of food systems transitions, on the other hand. Moreover, options fitted to contrasted regional and local contexts, as well as adverse effects and risks associated to transitions must be better studied and specified.

Transformations are essentially bottom up, while socio-economic pathways and integrative assessment models start with assumptions at global scale. Transformations of socio-technical processes, including the development and networking of niches and the effects of systemic lock-ins, have to be better understood and integrated into the design of scenarios and pathways at global scale.

To cope with this increasingly complex and uncertain international context and to answer the urgency of the situation (recognized on 12 december 2020 by the UN Secretary General António Guterres, as a state of climate emergency) international assessments in their current format need to evolve, or to be complemented, to address issues such as:

i/ Accounting for even greater uncertainties over the coming decades than assumed so far, including tipping points, low probability and high impact events, as well as a broader range of economic scenarios (including possible economic contraction);

ii/ Assessing combinations of integrative response options that could allow reaching several SDG targets at a time. To this end, a back-casting approach could be used by filtering combination of response options to current and future challenges that would allow meeting multiple SDG targets.

iii/ This type of assessment could be developed starting with global scale, but also benefiting from bottom-up studies involving stakeholders, and assessing transformation pathways in contrasted countries and regions.

Improve the evidence-based dialogue across scales

Lessons from the dynamics of local innovations in initiating and pursuing transitions, must be integrated in the depiction of local, national, regional and global trajectories. For that purpose, the dialogue between place-based innovation approaches for transformative change and tests of the adequacy between local/national transition pathways and global (e.g. environmental, social, One Health) ambition has to be organized.

In particular, to improve modelling and foresight on intertwinned challenges, interdisciplinarity, transparency in model design, access to data along FAIR principles[1] and an exploration of the sustainability space without a priori are necessary. This includes the exploration of factors related to population, diets, land use, production modes, trade rules and exchanges modalities; and of uncertainties of all kinds.

Enable conditions for the production of actionable knowledge to engage in deep transformations at scale

The strategy requires to develop experimentations and iterative processes for the design and deployment of place-based solutions supported by relevant and coherent policies and measures allowing transformations to take place at scale in a long term perspective.

1. Findability, Accessibility, Interoperability, and Reuse of digital assets.

To allow and support first experimentations, and second the deployment of mature projects on the ground in a coherent manner and above critical scales, in order to initiate transitions, funding agencies and research organizations have to develop new evaluation criteria and operation modes as well as promoting a culture of impact. They also have to consider themselves no more as 'starting points' for projects and programmes toward sustainability, but rather as facilitators. This requires supporting local innovations, developing cocreation of knowledge, participatory science and place-based living labs, in collaboration with stakeholders.

For that purpose, a massive development of interdisciplinary and transdisciplinary research, will be key. But to make it happen, the prior understanding of the institutional, organisational and cultural blockages and of the ways to overcome them, is necessary.

In particular, developing methods helping researchers to precisely identify options or targets for the desired transformations; building potential transformation pathways to reach these targets; creating as soon as possible partnerships (in research and with potential users) to increase the probabilities of success; identifying potential contributions of knowledge generated in research projects/programmes, as well as the associated levels of uncertainty and account for uncertainties in the design of transformations, are required.

Revisit the relations between science, society and policy

Scientific knowledge is vital for the democratic debate and has to stay an important part of the culture. In addition, in recent decades, science has been increasingly and urgently called upon to provide precise and, if possible, rapidly available actionable knowledge to answer vital societal questions such as energy sources, food production, climate changes, global warming, or the treatment or prevention of infections (polyomielitis, AIDS, H1N1, coronavirus) and pathologies (cancers, neurodegenerative diseases). However, we have to recognize the diversity of forms of interactions between scientists as experts with other components of the society, together with policymakers, decisionmakers, stakeholders, media, public and private actors, NGOs, think tanks and citizens. Therefore, their influence results from a complex process, especially for questions such as systemic transformations which have large degrees of uncertainties as well as high and conflicting stakes.

Pursuing multiple socio-economic-environmental-planetary objectives with our current configurations of capacities, processes, and institutions will not be possible. On top of the changes mentioned, the COVID-19 crisis has highlighted the need for a major shift in the way research organisations interact with other components of society: humility (not hubris); hope (not fear); diversity (not singularity); mutualism (not hierarchy); equality (not superiority or hegemony); precaution (not calculation); flourishing (not growth); and care (not control).

Strengthen international cooperations for science and for science-policy interface

When looking at complex challenges, international engagement and cooperation have become increasingly important for several reasons:

- The interdependency across countries and world regions has increased over the last decades by the rise in international trade and international travels, by the globalization of supply chains, technologies and financial markets and by anthropogenic global environmental changes. No single country or world region can tackle major issues such as climate change, loss of biodiversity, land and water resources degradation, malnutrition and emerging infectious diseases.
- Scientific research increasingly involves international collaborations. Literature shows that internationally coauthored articles tend to be more highly cited than national coauthorships or sole authored work and that international research tends to be more interdisciplinary. However, there are multiple barriers to international collaboration, including lack of funding for international work, restrictions on material and data sharing, differences in academic standards and perceived bias against scholars from emerging or developing countries.
- To address more efficiently the 2030 Agenda, revisiting international cooperation across research and higher education organizations will be pivotal. Leading research organizations from contrasted world regions could agree on a shared vision concerning the main challenges for land and food systems and the role of science and technology to overcome these challenges. A network (or alliance) of these organizations could be initiated across world regions to address interlinked SDGs, their synergies and trade-offs and to develop actionable knowledge supporting place based innovation.
- To support such profound changes, adapted innovative funding mechanisms and cooperation across national or regional funding agencies are indispensable, also to ensure the involvement of research organizations from low income countries.

The findings of this report are summarized in figure 1 below. It shows how the current efforts undertaken by UN for Agenda 2030, in dialog with governments and supported by international expert panels, is gradually evolving to support a polycentric governance on key challenges, that requires:

- Improved assessments targeting combinations of responses to reach multiple SDGs
- Pathways and models better reflecting large uncertainties and connections across scales
- International coalitions supported by research networks and focusing on integrative responses to multiple interconnected SDGs to deliver place based innovation.

The Scientific Committee

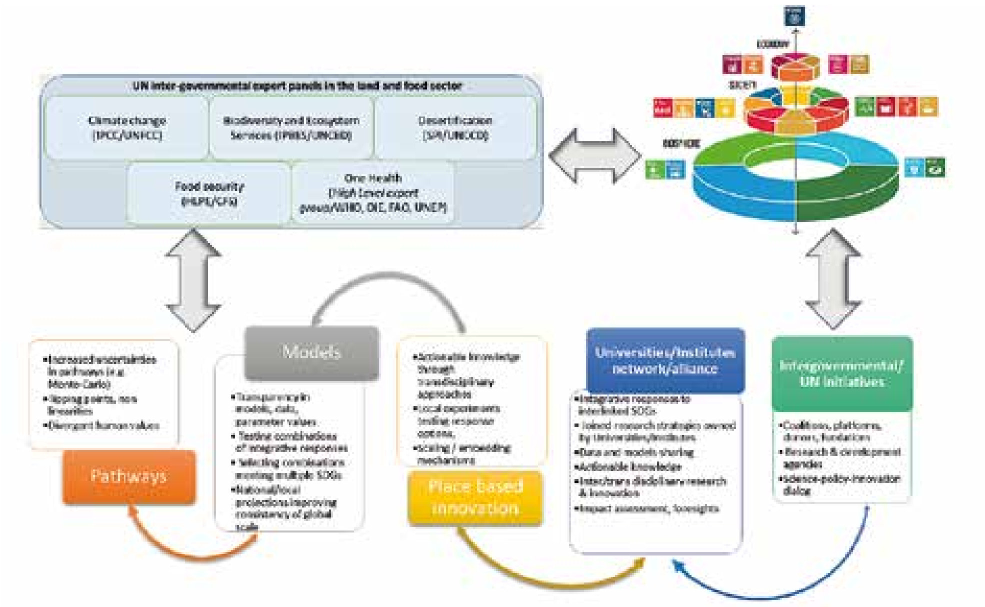

Figure 1. Towards systemic change in research, innovation, science-policy-society dialogue and international cooperation to support the 2030 Agenda and engage in a transformation towards the sustainability of food systems and land management. Key international expert panels (top left) address challenges as the 2030 Agenda (top right, after Rockström & Sukhdev[2] 2016) requires the development of integrative solutions. Research should engage in the exploration of transformational trajectories towards sustainability, model combinations of response options bringing co-benefits for several SDGs (bottom left) and implement transdisciplinary experiments aimed at implementing implementing transitions in the territories. This requires (bottom right) a strengthening of cooperation between research organizations with the support of intergovernmental coalitions.

2. https://www.stockholmresilience.org/research/research-news/2016-06-14-how-food-connects-all-the-sdgs.html

Acronyms

AgMIP	Agricultural Model Intercomparison and Improvement
CFS	UN Committee for Food Security
CMIP	Coupled Model Intercomparison Project
GAIN	Global Alliance for Improved Nutrition
GSDR	Global Sustainable Development Report
HLPE	High Level Panel of Experts
IAM	Integrated Assessment Models
IDDRI	Institute for Sustainable Development and International Relations
IIASTD	International Assessment of Agricultural Science and Technology for Development
IPBES	Intergovernmental Platform on Biodversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPSP	International Panel on Social Progress
ISIMIP	The Inter-Sectoral Impact Model Intercomparison Project
JRC	Joint Research Center, European Commission
MEA	Millenium Ecosystem Assessment
MDG	Millennium Development Goal
UNEP	UN Environment Program
SDG	Sustainable Development Goal
SSP	Shared Socio-Economic Pathway
SPI	Science-Policy Interface
STI	Science, Technology and Innovation
UNCBD	UN Convention on Biological Diversity
UNCCD	UN Convention to Combat Desertification
UNFCCC	UN Framework Convention on Climate Change

Report

In an unprecedented context of urgent and interconnected challenges, this report discusses how research, scientific expertise and foresights could be reshaped to support evidence based policies for a deep societal transformation in food systems and in the land sector.

A brief look back at the contribution of research to agriculture and food in the past fifty years contributes to set the stage. Over this period, while human population doubled, total world agricultural production has been multiplied by 3 whereas land productivity by 2.6 and labor productivity by 8 (Dorin 2014). It is generally considered that roughly 50% of this increase may be attributed to R&D (Alston et al., 2009, Fuglie et al., 2020). However, the impact of R&D has been very different according to countries. Subsahelian African countries and, generally, smallholders in poor countries have less benefited from technological change, which contributed to an increase of the gap between high- and low- income countries. Furthermore, the agricultural production became more dependent on oil and chemical compounds, which increased its environmental footprint. Also, during the last 20 years, the rate of agricultural productivity increase has slowed markedly whereas the cost of R&D has sharply increased (Barrett et al. 2020). New challenges also call for changing technological trajectory of research towards the Sustainable Development Goals (SDGs). This is why this report considers that more research will not be enough. A key message of this report is that we need to produce actionable knowledge oriented toward these goals and contributing to transformative changes.

The current COVID-19 pandemic illustrates the fragility of our health, social and food systems, and their multiple interdependencies, creating cascading risks, at scales ranging from local to global. This global crisis speaks to the underlying causes of pandemics, which are linked to the same global environmental changes that drive biodiversity loss and climate change[3], and to the co-morbidities that are largely related to unhealthy behavior, diets and obesity (such as diabetes and high blood pressure). It also highlights that the interface between scientific expertise, and political decision-making should be strengthened, in order to better anticipate and prevent new emerging threats, to prepare for future crises and to organize early responses.

In this context, research should not only aim at informing an integrative and system-based vision of future landscapes, e.g. of land management, food and water systems and associated activities, but also include the economic, social, health and well-being outcomes that they generate (Raworth, 2017); and furthermore contribute to designing transition pathways and identifying both lock-ins and levers for change. We should explore how, in the wake of the COVID-19 pandemic, science could more efficiently provide actionable knowledge and better contribute to new foundations that might be built internationally for enhancing the resilience of people, social systems, life and Earth by 2050 and beyond. **We argue that working towards transformation is the best way to enhance resilience and we explore the role of science in this process.**

We know that land-based systems are exposed to multiple, overlapping stresses, including climate change, desertification, land degradation, biodiversity loss, water scarcity and pollution, food insecurity, poverty, malnutrition and both non-communicable and communicable diseases, including those with an environmental or zoonotic origin. Transformative solutions addressing these intertwined challenges are needed (Agenda 2030[4], 2015; The World in 2050[5]; IPCC 2018, IPCC 2019[6]; IPBES 2019[7]; GSDR 2019[8], Sachs et al., 2019), but the understanding of the complexity and global systemic interconnexions of these processes needs to be enhanced. Our understanding of the new kinds of evidence that could bring about major socio-technical transformations at different scales of action, ranging from local to global, is also insufficient, as is our appreciation of the potential trade-offs between scale-specific processes. Moreover, cascades-of-events crises require a critical review of the way national, regional and international research, expertise and action are organised and mobilized for public policy decisions.

After identifying lessons learned from international assessments and foresights in section 1 and emerging approaches for research and knowledge for transformative change in

3. IPBES Workshop on Biodiversity and Pandemics, Workshop Report, Executive Summary, July 2020.

4. https://sdgs.un.org/2030agenda

5. https://iiasa.ac.at/web/home/research/twi/TWI2050.html

6. https://www.ipcc.ch/sr15/ https://www.ipcc.ch/srccl/

7. https://ipbes.net/global-assessment

8. https://sustainabledevelopment.un.org/gsdr2019

section 2, we consider in section 3 the role of international cooperation.

1. What have we learned from international expert assessments and foresight studies on grand challenges? How could assessments be improved in the future?

In this section, we discuss how international expert assessments and associated foresight and modeling studies for land and food could be further developed, and possibly reframed, to progress on Agenda 2030.

Over the last 50 yrs (e.g. since the United Nations Conference on the Human Environment in Stockholm in 1972), in response to environmental concerns, international and intergovernmental institutional arrangements and organizations have been created through conventions, agreements, programmes (UNEP) and expert panels. Scientists (together with NGOs and think tanks) were instrumental in this process by actively developing the evidence-base, providing the interface between science and policymaking through intergovernmental expert panels (e.g., IPCC for UNFCCC, IPBES for UNCBD, IPSP), and fostering the establishment of expert processes (e.g., MEA, IAASTD, GSDR) and bodies attached to UN and intergovernmental bodies (e.g., HLPE for CFS). The panels that were created are framed within contrasting institutional and political contexts, organized and funded in different ways, and working with similar but somewhat different methods. They have generated rich and influential knowledge syntheses, showing key advances but also large gaps in our overall understanding of interconnected global challenges.

How should we revisit the understanding gained from international assessments for better addressing the trade-offs and synergies across SDGs and better assessing response options for land and food systems to interconnected challenges across scales? Should we envisage a next generation of assessments framed differently? How do we see the next generation of pathways and of assessment models and how could they account for divergent human values? How could highly diverse scientific communities better contribute to such renewed assessments?

1.1. International expert assessments and their scientific literature base

Over 1990-2020, the number of scientific publications on biodiversity and ecosystem services, climate change, land degradation and desertification, food systems, food security and malnutrition has been multiplied by a factor between 14 and 234, whereas multiplicative factors were much lower, between 3 and 5.5, in the broader scientific literature concerning the agriculture, food and environment fields (Figure 2). Hence, within 30 years the scientific literature relevant for assessments performed by expert panels, such as IPCC, IPBES, the SPI of UNCCD and HLPE, has flourished at an un precedented pace. To which extent was this rise caused, directly or indirectly, by the framing of new scientific questions by assessment reports is unclear. For instance, part of this increase could be due to the launch of new journals on these issues. Nonetheless, questions framed by expert assessments have triggered novel research approaches, including reviews, meta-analyses, scenarios and model developments. This process has often been institutionalized with the development of international model inter-comparisons cycles (e.g. CMIP for climate models, AgMIP for agricultural models, etc.).

Interestingly, in 1990, there were very few publications dealing with several of the challenges listed in Figure 2: only one publication dealing with three challenges (climate change and biodiversity and land degradation/desertification) was found. In contrast, in 2020, 390 referenced studies dealt with the three interlinked challenges and about 4,600 more dealt with two of these challenges at a time. Hence, not only did the scientific literature expand rapidly about major environmental challenges, but moreover interconnections across challenges became increasingly studied. The rise of systemic thinking is also apparent in the gradual adoption of the food system (58 and 283 papers in 1990 and 2020, respectively) and One Health (from 26 to 993 papers over 1990-2020) concepts. Other cross-field integrative concepts now widely in use were developed only 10 years ago: planetary boundaries, a concept first published in 2009 (Rockström et al.) and the nexus between water, food and energy that became visible in the literature in the 2010s. Hence, the interconnectedness of global anthropogenic challenges gained full traction after the start of the XXIst century, coinciding with the definition of the Anthropocene by Paul Crutzen in 2002.

The last three decades have also seen an exponential rise of scientific papers devoted to earth system models (first coupling geosphere with atmosphere, and then also with the hydrosphere and to some extent wit the biosphere) and to integrated assessment models coupling biophysical and socio-economic processes (data not shown). The number of processes and the spatial resolution of these models have been gradually increased. This has allowed projections driven by pathways (e.g. socio-economic pathways, carbon pathways for greenhouse gas emissions and for the land sector biodiversity, land use change, agricultural and food pathways) to be increasingly used by international expert assessments. Such projections are instrumental to explore contrasted future landscapes at global and regional scales and across time horizons ranging between 2030 and the end of the century, or beyond for earth system models.

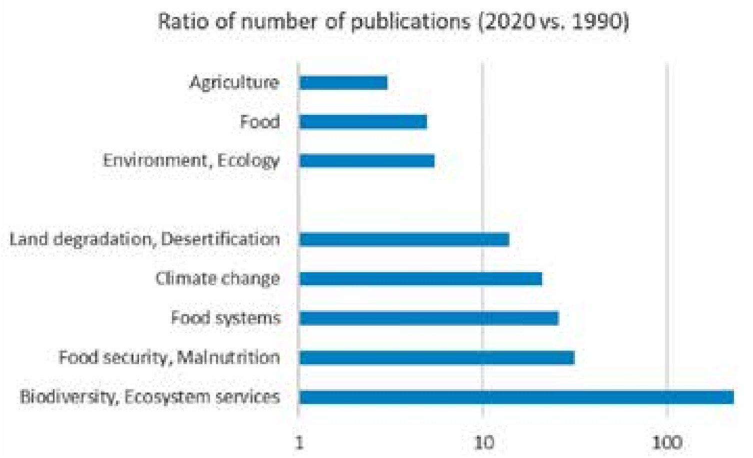

Figure 2. Ratio of number of publications in 2020 compared to 1990 for selected literature fields (Agriculture, Food, Environment and Ecology) and for 5 global challenges addressed by international expert panels. Note the log scale used for the horizontal axis[9]. Source: Web of Science, Clarivate Analytics©, All databases.

9. Key Words used for Topics in search equation (Figure 1): environment* OR ecologic* ; food ; agricultur*; biodiversity OR "biological diversity" OR "ecosystem service*" OR "nature contribution to people"; food system*; climat* change; ("land degradation" OR desertification OR "soil degradation" OR "soil erosion" OR "soil carbon" OR "soil organic matter" OR "soil organic carbon"); (("food security" OR "food insecurity" OR "hunger" OR "stunting" OR "malnutrition" OR "obesity" OR "undernourishment") NOT (mouse OR animal* OR cell* OR tissue*)) [excluding]: RESEARCH AREAS: (ENDOCRINOLOGY METABOLISM OR PHYSIOLOGY OR SURGERY OR BIOCHEMISTRY MOLECULAR BIOLOGY OR PHARMACOLOGY PHARMACY OR RADIOLOGY NUCLEAR MEDICINE MEDICAL IMAGING OR MEDICAL LABORATORY TECHNOLOGY)

1.2. A renewed policy context for international expert assessments

While highly successful in terms of triggering science advances, the jury is still out concerning the extent of the policy impacts of international assessment reports. For instance, we have emitted more[10] CO_2 since the creation of the IPCC in 1988, than between 1750 and 1988. As pointed by Mike Hulme (2020): "Since the first Earth Day 50 years ago, it has become clear that it is easier to generate scientific insight into the ways human systems are altering the planet than it is to redirect those human systems to lessen their planetary impact. At the heart of this conundrum are divergent human values". Indeed, divergent human values, as well as conflicting interests, the role of lobbies and of bias in media reports (Farrell et al., 2019; Lamb et al., 2020) have contributed to weaken the uptake of these assessments.

In 2012, at the UN Conference on Sustainable Development - or Rio+20 - Member States decided to launch a process to develop a set of Sustainable Development Goals (SDGs), building upon the Millennium Development Goals (2000) and the three pillars associated with the concept of sustainable development, introduced by the Brundtland's report (1987). In September 2015, during the celebration of the 70th anniversary of the UN, Agenda 2030 a plan of action for people, planet and prosperity was adopted by all Member States, with a view that bold and transformative steps are urgently needed to shift the world onto a sustainable and resilient path, while leaving no one behind. This universal agenda has 17 Sustainable Development Goals and 169 targets.

In fact, many scientists, policymakers and governments are unclear about how to operationalize such a complex agenda. Many find 17 goals and 169 targets overwhelming, and because of this complexity crucial issues like inequality or climate change may be pushed aside. Beyond the limited ability of governments, businesses and other actors to pursue a large number of goals simultaneously, there are also analytical challenges. Many goals are interdependent, so the SDGs cannot be pursued through 17 discrete strategies – one for each goal (Sachs et al, 2019). Several studies have attempted to assess synergies and tradeoffs across SDGs targets (e.g. Pradhan et al., 2017).

Across the goals, 42 targets focus on means of implementation, and the final goal, Goal 17, is entirely devoted to means of implementation. However, as shown by Stafford-Smith et al. (2017), these implementation targets are largely silent about interlinkages and interdependencies among goals. Frameworks used for the systematic conceptualization of the SDGs and the interlinkages and interdependencies between them were reviewed by Breuer et al (2019), who pointed at limitations, caused by methodological and conceptual challenges for the empirical analysis of SDG interlinkages, by

10. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions context sensitivity at national scale and by the need for critical ranking of goals when implementing Agenda 2030.

The ambition of the Global Sustainable Development Report (GSDR, 2019) was to move beyond thematic assessments in order to contribute to the achievement of the SDGs in nexus and to the design of pathways to do so. However, it is unclear how the six entry points proposed by this report can support action on the ground.

The need to move beyond thematic assessments has also been echoed in advocacy and expert panels and think tanks (e.g., Ipes Food, EAT Lancet/Rockefeller Foundation, IDDRI, Malabo Montpellier Panel) reports, for instance in the case of food systems. In these reports, food systems are increasingly acknowledged as a nexus crossing different sectors and dimensions of sustainability. Food systems (HLPE, 2017) are seen as strong levers to address the 2030 Agenda for Sustainable development (Caron et al. 2018), while also being increasingly questioned for their negative externalities (e.g., health and environmental impacts, global trade versus local production). The Water-Energy-Food nexus has also been recognized as a valid approach for sustainability-directed research (Kurian, 2017).

While the Agenda 2030 provides a positive depiction of future changes that are needed, assessment reports increasingly question this narrative. For instance, most emission scenarios consider that we will overshoot GHG emissions needed to meet the targets set in the Paris Agreement and large negative emissions will be required to achieve climate stabilization later in the century. By shifting from the Millennium Development Goals (to be reached by 2015) to the SDGs with 2030 as time horizon, a new set of goals has emerged, with little accountability and insufficient analysis and understanding of why past goals and targets were not achieved. Indeed development goals, while inspirational, are often overly ambitious and some of them are very difficult to reach, or even unlikely to be achievable, as illustrated by the following examples:

- With current trajectories, it is highly unlikely that the world will eliminate hunger and malnutrition in all its forms by 2030, of which the SDG2 calls for (Fanzo, 2018, Kharas and McArthur, 2018).
- If the number of people living on less than $1.25 a day has been reduced from 1.9 billion in 1990 to 836 million in 2015, the target of halving the proportion of people suffering from hunger by 2015 (MDG1) was missed.
- The child mortality rate has been reduced by more than half over the past 25 years – falling from 90 to 43 deaths per 1,000 live births – but it has failed to meet the MDG4 target of a drop of two-thirds by 2015.

Increasingly, uncertainties about reaching the SDGs are mentioned including the possibility of irreversible bifurcations due to global warming (Steffen et al., 2018), loss of biodiversity and ecosystems degradation (Barnosky et al., 2012), land degradation and breadbasket failures in several regions in conjunction with water crises. Moreover, the rise in health risks both from diet-related non-communicable diseases and from emerging infectious diseases (often of zoonotic origin, or caused by anti-microbial resistance) fuel the narrative of a collapse. In such a narrative, an increasing part of the world GDP would be swamped by climatic, environmental and health degradation, coupled with a rise in poverty, conflicts and migrations and prolonged disruptions in trade, economics and politics (Albert, 2020; Herrington, 2020).

Nevertheless, knowledge, capabilities, funding and institutions could be mobilized on unprecedented scales to tackle interconnected challenges.

To cope with this increasingly complex and uncertain international context and to address the urgency of the situation (recognized, on 12 december 2020, by the UN Secretary General António Guterres, as a state of climate emergency), international assessments have helped shaping the agenda and framing the analysis but are possibly not sufficient, or need to evolve, to address issues such as:

i/ Accounting for even greater uncertainties over the coming decades than assumed so far;

ii/ Assessing combinations of integrative response options that could allow reaching several SDG targets at a time;

iii/ Assessing pathways towards sustainability not only in a top-down way, starting with global scale, but also through bottom-up integration of local/national visions thereby contributing to a polycentric governance of key challenges (Sengers et al., 2020) and of transitions towards sustainability.

1.3. Renewing assessments

1.3.1 Accounting for increased uncertainties

The current global disruption caused by the COVID-19 pandemic shows how a single virus spillover can disrupt social, political and economic trends worldwide within just a few months. This crisis has unprecedented impacts since the Great Depression with a global growth reduction by 4.4% in 2020, a rise in poverty and inequalities (IMF, 2020) and a 7% reduction in global annual CO_2 emissions for the first time since several decades (Le Quéré et al., 2020).

It further highlights the strong interconnections between health, biodiversity, climate change, food, socio-economic, human and policy dimensions and the key limitations in our understanding of appropriate response options. It also demonstrates how we live in a telecoupled world (Liu et al., 2016) and confirms the need to move beyond thematic assessments and to generate system-based, forward-looking intelligence.

The COVID-19 pandemic has also shown that in times of pressing crisis, governments around the world have been ready to take drastic measures with large distributive consequences. Like in the fable of the "boiling frog", it seems that responses to a sudden threat that show rapid impact (COVID-19) are of greater magnitude than responses to slowly building threats like climate change and the loss of biodiversity.

Projections by expert assessments may convey a false sense of predictability, i.e. projections may seem to predict a possible future. This can be, in part, corrected by reporting a range of results for contrasted pathways and contrasted models. For instance, more than eighty articles quantifying the effect of various response options in the future, covering a variety of response options and land-based challenges ranging from global to regional to country-level, were reviewed by the IPCC Special Report on Climate Change and Land (2019). This stresses the necessity to better include low probability and high impact events in storylines, for climate change for instance. This requires improving our understanding of the changing state of the climate system and to better include regional climates and hazards, as well as a comprehensive risk approach including compounding and cascading risks and a better understanding of climate tipping points (Lenton et al 2019). Indeed issues of tipping points and surprises due to feedbacks were already highlighted (e.g. IPBES, 2019 and IPCC, 2013, 5th assessment report) but they are generally poorly accounted for in most quantitative scenarios.

Moreover, a much broader range of economic trends need to be explored, with their associated implications for e.g. food demand, land use change and demography. Most prospective models are built assuming that countries are experiencing economic growth and/or are at peace. If resilience is our target, the robustness of predictions should be tested more systematically against a scenario in which countries are in economic contraction with resources becoming scarce (see e.g. foresight for 2035, National Intelligence Council, 2017) and with increased conflicts and wars related to food and water insecurity (SOFI, 2017).

Radical transformation pathways (see Box 1 below for a definition of transformative change) may also need to be explored further, including lifestyles, land use, biodiversity, water use and food systems. Most socio-economic pathways explored so far have not been based on radical changes in consumption patterns since such changes are seen as unlikely. Most models assume that there is a positive relation between income increase and meat consumption, a crucial hypothesis which is increasingly challenged. While exploring such pathways at the global level is needed, at the same time there is room for contrasted options at the local, national and regional scales, including leapfrogging (see UNIDO, 2019) and the role of context-dependent innovation.

1.3.2. From scenarios and pathways to the assessment of integrative responses to reach multiple SDGs

Integrated Assessment Models (IAM) and associated scenarios have been central in the dynamics of scientific communities and assessments at science policy interfaces (e.g., the Millennium Ecosystem Assessment, IPCC reports and assessments informing the elaboration of the Montreal Protocol and its subsequent amendments). IAMs have been coupled to multiple socio-technical pathways connected to a variety of carbon, biodiversity, food, water and health transition scenarios (Van Vuuren et al., 2017).

IAMs have been very useful to connect modelling efforts in different key areas (climate, ecosystems, water resources, energy systems, land use, economic policies…) around a standardized set of scenarios. They thus have had a wide political audience.

However, inter-connection and interoperability of models is very complex and needs long-term investment. Therefore only few institutions/research teams can afford such an investment. This has led to a de facto « oligopoly » and a possible lack of pluralism in modelling approaches. It may also create path dependencies, with large difficulties to question or change the modelling framework to adapt to new knowledge, new theoretical questions and new societal issues.

Moreover, the transparency of IAM models (i.e. access to published equations, data, parameter values and code) is at best heterogeneous and barriers to access models may be limiting their use and the discussion of their many assumptions by the scientific community. On the other hand, some programs (e.g. AgMIP, ISIMIP) have encouraged the inter-comparison, discussion and development of IAMs for agricultural and land use issues.

Given the large uncertainties associated to the elaboration of pathways to 2030 and 2050, progress should be made, in particular by developing simpler models covering the full nexus of land, water, energy and food systems and associated challenges, and exploring in a fully transparent way an extended spectrum of future global pathways while assessing trade-offs and synergies across SDG targets.

To this end, a back-casting approach could be used to produce pathways allowing to meet multiple SDG targets, for staying within planetary and social boundaries (Raworth, 2017) . This approach requires to filter/produce a relevant combination of response options to current and future challenges.

This next generation of assessment models could evidence which coordinated changes in land use and in food systems would be required to meet multiple SDGs targets. This type of assessment would not only be developed starting with global scale, but could also benefit from bottom-up studies involving stakeholders, and assessing transformation pathways in contrasted countries and regions.

1.3.3. Coupling top-down and bottom-up approaches in assessment methodologies

Most assessments at global scale do not allow to sufficiently understand links with local and national scales, where they are needed. For example, the global assessment approach in the EAT Lancet report (2019) failed to determine how food is produced regionally and the bioavailability of nutrients from available food items, resulting in local diets which were unachievable and deficient. In the same way, most assessments do not reconnect the time frames between scientific knowledge and political decisions. While global scale assessments are needed, their translation to national, and maybe even subnational consequences is needed. It requires a national/ regional vision that addresses the integrated outcomes of these assessments into a vision that is applicable to come into action (Béné et al., 2020). This questions how we reconcile policy agendas which are still largely set at national and local scales and assessments which are mostly framed at global scale.

Although global transformation relies on local change and on interactions between different scales, assessments are usually carried out at the global and regional levels, sometimes at the national level (e.g. national level assessments in the USA). Therefore, top down approaches towards sustainability need to be complemented by bottom-up approaches, where each country/territory defines and discusses its own pathway to sustainability, given its specific history, resources, situation and perspectives. The latter approach is closer to the real political arbitrages that determine social and economic decisions. The former is needed to ensure global consistency in the aggregation of national/local transition pathways and is also the good position/method to catalyze rapid changes. How both approaches can be coupled remains to be further explored (Schmidt-Traub et al. 2019).

Achieving the global agenda will depend heavily on successful national-scale implementation, which requires the development of effective science-driven targets tailored to specific national contexts and supported by strong national governance. For instance, Climate Change Committees act as independent public bodies to advise on tackling and preparing for climate change in UK[11], in France[12] and in several other countries and review the progress made in the implementation of long-term national strategies. Indeed nations require globally coordinated, national-scale, comprehensive, integrated, multi-sectoral analyses to support national target-setting that prioritizes efficient and effective sustainability interventions across societies, economies and environments (Gao et al., 2017).

11. https://www.theccc.org.uk/

12. https://www.hautconseilclimat.fr/en/

2. Emerging approaches for research and knowledge for transformative change, advances, gaps and challenges

We know that to address the challenges identified, incremental change will not be enough and that systemic changes will be necessary. The notion of *transformative change* is increasingly used to point out that a radical change of diverse interrelated socio-technical systems is needed (Box 1).

Box 1. Transformative change

Transformative change may be defined as radical innovation at scale, i.e. not just doing more or less but doing things differently (IPBES, 2020). This notion is close to the concept of transformation defined by Patterson as "fundamental changes in structural, functional, relational, and cognitive aspects of socio-technical-ecological systems that lead to new patterns of interactions and outcomes" (quoted by Scoones et al. 2020).

In this perspective transformative change is global in the sense that it does not only involve technological change and modes of production but also changes in modes of consumption, culture, infrastructure, institutions, regulation, as well as distribution of power and wealth. Historical analysis of previous transformative change is instructive. For instance, Kanger and Schot (2019) refer to the case of industrial revolution to understand the double challenge of environmental degradation and social inequality we are confronted to. *Deep transformation* (the concept coined for this type of change) is a long and complex process characterized by changes in different sociotechnical systems (e.g. agiculture, energy, transportations, etc.) and also changes in metarules (e.g. property rights, trade agreements, international law, etc.). The current deep transformation which is needed is confronted to the strength of the incumbent sociotechnical systems.

The extent to which transformative change may be intentional is a point discussed in the literature (Scoones et al. 2020). Anyhow, deliberate governance of transformative change is necessarily tentative because of the high uncertainty, complexity and ambiguity of processes involved.

We have learned from history that governing transformative change is extremely difficult since this requires not only changes of practices, of technologies, but also changes in power relation and wealth distribution. For example, the substitution of animal proteins by plant-based proteins does not only require changes in diets but also new cropping systems, plant varieties and seeds, changes in food processing and retailing. The animal production value chain will also be challenged, with negative implications for producers and land managers, and with further implications regarding waste and nutrient cycling (e.g. from plant-based by-products which traditionally were used as animal feed; preserving soil fertility without increased inorganic fertilizer use). And ultimately consumers choices should evolve, which constitutes an important challenge responsible for many past and current failures.

Addressing transformative change has several implications for research governance and practices. **First, we cannot continue to rely on a linear model of a science-policy interface -** "science speaks truth to power"[13]. We need to take seriously the complex and multiple interactions between knowledge and action. In many instances what is lacking is not more evidence, but action-able knowledge that may contribute to the necessary systemic changes.

to reach it - is not. But we can draw on previous experience and on foresight activities to figure out possible pathways and the various contributions of research.

To reshape the role of technologies, binary opposition of positivism versus rejection stances have to be overcome (Caron, 2020). This may involve redefining technologies, e.g. through inclusion and assessment of low tech and nature based approaches. Developments in other agendas are also often important to consider. For instance, in some contexts, nature inclusive agriculture requires developments in technology agendas, including e.g. robotics e.g. to support strip cropping. Thinking of how to reconnect such distant agendas can foster transformative innovation.

Box 2. Actionable knowledge

Simply stated, actionable knowledge is knowledge that allows actors to effectively implement their intentions (Argyris 1993). The concept of actionable knowledge has been elaborated by scholars belonging to different communities who were confronted to the gap between production of knowledge and effective action, mainly in organization studies, sustainability sciences and science-technology studies (Miller and Wyborn 2020).

In organization studies, the assumption is that action was embedded within the knowledge, such as creating knowledge specifically about which management action to take and how to implement it (Argyris 1993). More recent conceptualizations are discussed in the field of sustainability sciences. The knowledge-production process is considered as distinct from the realm of practice, where the science is tailored to inform an action, while not directly providing advice or details about which action to take and how (Mach et al. 2020).

Production of actionable knowledge is generally associated with co-production (Arnott et al. 2020), i.e. a process that closely associates producers and users of the knowledge. Importantly, the science of science has deeply improved our understanding of co-production of knowledge. Three key lessons are especially significant (Miller and Wyborn 2020):

1. Be inclusive in the diversity of participants, the power accorded to them, and the processes and objectives of co-production. Ensure that the institutions that enable co-production attend carefully to the credibility, legitimacy, and accountability this entails.

2. Acknowledge that co-production is a process of reconfiguring science and its social authority. Such processes require participants to be reflexive about the inherently political nature of producing knowledge in the service of changing social order at local to global scales.

3. Recognize that public engagement, deliberation, and debate will shape the content and relevance of knowledge and its ability to help construct and empower institutions to facilitate sustainability.

More globally, as shown by actor-network theory and innovation studies, the improvement of production of actionable knowledge requires to better understand the processes of translation of action to knowledge and knowledge to action (Joly et al. 2015). This may require implementation of adaptive management based on explicitation of theories of change (e.g. outline of impact pathways that allows to identify critical points) (Joly et al. 2019).

This implies improving our understanding of processes of deep transformation (Kanger and Schot 2019), their temporalities, the lock-in effects, and the way research can contribute to nurture desirable and sustainable dynamics. This also implies better understanding the different ways research can contribute to these changes, i.e. the various research impact pathways (Joly et al. 2015). Addressing societal challenges means that research has to be oriented toward identified objectives, for instance "zero pesticides" agriculture or water treatment for safe reuse in the frame of circular economy. Although the objective is known, the pathway – i. e. the process

The occurence of improperly framed scientific questions also requires further assessments. For instance, many research articles still claim that food security and deforestation can be fixed through agricultural yield increases, even though Norman Borlaug's land sparing hypothesis may not be verified (Pellegrini et al. 2018, Desquilbet et al. 2017). This is related to the way scientific disciplines are shaped. For instance,

13. Collingridge, D. & Reeve, C. (1986) Science Speaks Truth to Power: The Role of Experts in Policy Making. Frances Pinter, London.

few plant geneticists and agronomists are aware of Jevons paradox[14] in economy. This calls for more cross-fertilization between social sciences and experimental sciences, upstream of the definition of scientific questions.

Ecological theory and its applications in ecological networks have revealed the importance of nodes and links in the maintenance, evolution and resilience of natural ecosystems, with numerous nodes and ties at different spatial layers precluding better stability and resilience to external menaces and shocks. The strong inter-connections that exist today between local and global scales (e.g., intercontinental transportation of people, domestic animals, goods and pathogens, world prices regulation, transnational industries, commodity markets) have contributed to decrease local resilience and increase society vulnerabilities by destabilizating the numerous links that existed locally previously. Ideally, ecological fallacy and tools could be used to better comprehend how to generate more resilience, sustainability and fair sharing in complex networks of economic exchanges and trade.
Last, particular attention should be paid to the introduction of variables made 'invisible' in international assessments and foresight studies: notably, labour intensity, the structural transformation of farms – labor versus capital versus land intensity / productivity (Dorin & Joly 2020 , Schwoob, Timmer et al. 2018). There are also other important factors as beliefs, values, policy conceptions[15] which may not be sufficiently integrated into these models.

This also implies seeking **transformative change in knowledge production** as the current way knowledge is produced may be a part of the problem. We certainly have (inter alia) to improve our ability to perform interdisciplinary and transdisciplinary research, and benefit from participatory research including co-design of research agendas and citizen science.

2.1. The need for research to address societal challenges is taken seriously in policy arenas but it lacks real implementation

The need for research and innovation to address grand societal challenges is widely acknowledged. It is considered as a key issue at the OECD Global Science Forum as well as in private foundations or global corporations. Since 2010, many countries launched research programmes for that purpose. The European H2020 research framework dedicated 45% of its budget to Grand Challenges. During the preparation of the next Horizon Europe framework programme, it has been decided to go one step further in this direction with the design of "missions". The Lamy's Report proposed a mission-oriented, impact-focused approach to address global challenges (Lamy, 2017). The Report *"Governing Missions in the European Union"* claimed for a bold strategic approach to improve the ability of research and innovation to address societal challenges and speed up innovation processes (Mazzucato 2018).

Mission-oriented research is not new. Among others, the Manhattan and the Apollo projects are well-known historical examples of research mobilization to address important societal challenges (Foray et al. 2012). However, two characteristics make the difference when addressing grand societal challenges. Not only applied research and technological increments are required, but also new innovative solutions that involve frontier research. Therefore, it is not only a matter of technological research and development. Second, addressing these challenges will require systemic changes in the complex value chains, including their consumption end, thus implying also social, organizational, institutional and policy innovation, as well as participatory or critical approaches in research (Kuhlmann & Rip 2018). These two dimensions of research for transformative change call for evolutions in both research governance and innovation policies (Weber & Rohracher 2012, Schot & Steinmueller 2018).

This call for research to address societal challenges is still strengthening in different areas, including agriculture, food, management of natural resources, or health. The European Green Deal sets new important imperatives that should translate in research orientations (Sonnino et al., 2020) and, for the first time, food and agriculture policy are addressed together and need to contribute to SDGs.

Unfortunately, evidence shows that research in this domain remains marginal (Ramirez et al. 2019). Interdisciplinary knowledge production is valued, but as a niche activity (based in and adjunct to disciplinary knowledge production). And transdisciplinary knowledge production remains a proto-niche, poorly valued in the knowledge and institutional system. This situation is due to cultural and organizational lock-ins (Den Boer et al., 2020):

- Systems of evaluation and promotion in discipline oriented departments in universities;
- Scientific cultural tradition of the hypothetico-deductive approach through experimentation, which reduces the fields of research to lab experimental studies and therefore may limit the temporal and spatial dimensions of analysis;
- Siloed funding agencies constrained within disciplines, funding systems locked into an elaborate system of peer

14. The Jevons paradox occurs when technological progress or government policy increases the efficiency with which a resource is used, but the rate of consumption of that resource rises due to increasing demand.

15. Report "Understanding our political nature. How to put knowledge and reason at the heart of political decision-making" (JRC – 2019).

review and project funding, where funders are administrators and not strategic actors;

- Short-term performance pressures and excessive focus on little parts of complex systems, with possibly less attention to strategy and long-term value creation. Traditional programs and projects may have an excessive focus on short-term results at the expense of long-term interests;
- Interdisciplinary projects have often a single goal, instead of multiple.

Reflexivity and critical thinking are also lacking. For instance, whereas the IPBES report on pollinators recognizes agricultural policies as major drivers of biodiversity degradation through their impact on pesticide use, it does not sufficiently explain why policies to reduce pesticide use have failed for so many years. An "evaluation of public policies" type of research is indeed essential.

In this respect, crises (like the COVID-19) challenge the social order and may lead a wide diversity of actors (including incumbents) to revise their expectations. Hence, they have a high potential of destabilization and may open windows of opportunity for change.

2.2. What is expected from research and what are the required changes?

It is crucial to point out that the issues that are explicitly focused on with respect to transformation always are a tiny tip of the iceberg – with most other constituting characteristics remaining invisible below the surface of what is subjectively apprehended. In other words, when dealing with transformations, all categories are polythetic, not monothetic. In this light, transformation in any phenomenon, might simply be defined as "radical change in an unusual proportion of characteristics". Hence, it is crucial to acknowledge the distinctive set of characteristics of the processes that are at stake. Stirling (2010) suggested that whereas **simple changes** may be described as top-down, technical, orderly, invited engagement, knowledge-based fear-driven; **transformations** are best characterized as bottom-up, social and polycentric, unruly, uninvited engagement, values based, hope-inspired.

This said, we point out three main contributions of research to transformative change.

2.2.1 Systemic thinking, modelling and assessing

Global scenarios models are necessary for global coherence. They also **contribute to normative viewpoints** about economic dynamics, the integration of environment in economy (see next), values etc. Systems analysis obviously progresses, but there are yet huge research challenges as the use of technologies for analyzing big data providing new perspectives on system dynamics and behavior, better understanding of the dynamic of the systems and the interrelation of subsystems, resilience etc. And the SDGs have generated a lot of interest in accounting for these linkages in scenarios and models, in particular at the global level.[16] However, from a transformative perspective, things do not happen "globally" but in a fragmented and interconnected way that is challenging to model.

Hence, updating of global models (as the Earth3 model) and the interrelation with regional transformative models are needed. Technically it is possible to make various projections – cf. the work on the shared socio-economic pathways (SSPs')[17] and IIASA modeling activities on these issues at country level[18]. Indeed, work exploring the SSPs' fit at various scales produces useful knowledge for transformative change (see IPBES 2019, Chapter 5). Importantly, it is necessary to connect local and regional knowledge on processes concerning agriculture, environment and socio-economic systems, with the global or regional models.

Overall, what is at issue is the aim of modelling. We strongly suggest to design and use models as learning machines that allow to test the viability of normative scenarios in order to foster collective action aimed at transformative change, and not as truth machines that would define common pathways for system wide global adoption (Dorin & Joly 2020).

2.2.2. Better understanding processes of transformation and how research may contribute

Research is not only expected to produce knowledge and boost innovation, but also to help identify **transformation pathways** and to enlighten public debate and public decision making on related political choices. When one focuses on pathways, one of the important issues is to identify the different sources of lock-in and ways to unlock (Geels et al. 2017; Kohler et al. 2019).

Historical research shows that processes of deep socio-technical transformation usually take several decades. It is often assumed that the groundswell of socio-technical and governance experiments will 'scale-up' to systemic change. But the mechanisms for these wider, transformative impacts of experiments have not been fully conceptualised and explained. Sengers et al. (2020) describe and illustrate four 'embedding mechanisms' – (1) replication-proliferation; (2) expansion-consolidation; (3) challenging-reframing; and (4) circulation-anchoring – for entwined governance and socio-technical experiments.

16. https://iopscience.iop.org/article/10.1088/1748-9326/aaafe3/meta

17. https://www.sciencedirect.com/science/article/pii/S0959378016300838 and https://www.sciencedirect.com/science/article/pii/S0959378016300681

18. https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

The identification of lock-ins and the design of transformative pathways may speed up the process. We must learn from experiences, and especially from previous failures. For instance, the general failure of policies directed to the reduction of pesticides is both related to lack of adoption of alternative practices and to power relations in the value chains. Similarly, changes in dietary patterns are altered both by consumers preferences and routines, and by the political economy of the food supply chains. Historical research is needed to understand how dominant socio-cognitive frames (e.g., of disciplines, of concepts and theories, of training and education) and socio-economic regimes (e.g., values, interests, power relations, strategies) play – both consciously and unconsciously – and oppose the needed transitions. Any disruptive technology, just like a policy change, will imply winners and losers. When dominant actors are potential losers, they deploy complex strategies for opposing transitions.

For instance, a technology like precision agriculture is likely to have economic benefits with larger farms only, while digital agriculture may be scale neutral but questions the status of farmer's data (Basso and Antle, 2020). In the context of the loss of 90 percent of crop varieties from farmers' fields in less than a century (FAO, 2005), another example concerns novel investigation tools in plant genetics and biotechnology that offer previously inaccessible opportunities (Khatodia et al., 2016) and that may take contrasted pathways:

- uncovering crop diversity and exploiting genetic variability for plant breeding through genetic markers (significant investments, rather slow breeding, diversified genotypes tailored to local needs);
- engineering plants through novel biotech. e.g. CRISPR-CAS9 (large investments, stronger IP rights, faster to markets, large scale deployment since costs are high, no increase in diversity).

These different pathways to plant genetic improvement may have large implications in terms of agricultural development, crop rotations, social and environmental impacts.

Studies of socio-technical transformations also show that, whereas experimentations in protected niches occur frequently, generalization is much more difficult. This is one of the critical points to be addressed by research (Matt et al. 2017). Differentiating types of processes to support transformation at scale (e.g., mainstreaming, upscaling, outscaling) is particularly critical. In many cases the issue is not to replicate a standardized solution developed in one specific local context. It is rather to learn from the lessons of local solutions to help innovate in other contexts by overcoming similar yet distinct barriers and foster solutions that may be different. The process of agroecological innovation is illustrative of this challenge, where shared knowledge of problems and solutions does not lead to standardized solutions. Generalisation is also about finding new connections between different elements/components of a system. How can we produce pesticide free food in a manner that e.g. the seeds/plants and their diversity at landscape scale improve the soil health, and reduce the use of pesticides? What new biological pest control can we find to fit in such a system, etc.?

Making such a transformation at scale questions the possibility of economies of scale in innovation processes, and thus the funding model of research and innovation, actually more linked to the concepts of the knowledge economy than to the solutions of the Green revolution. Better understanding these processes will allow integration of devices/processes that contribute to overcome blockages, to be planned at the start of a programme or a project.

As mentioned above, generalisation is not only a matter of change of dominant design but also of dominant actors. Hence, it is both a matter of emergence of new socio-technical solutions and of breaking down the current existing production systems. How is it possible to create ' space' (literally as in sufficient land, but also financial space, space in the minds of producers, space in the public debate) for the new desired production and consumption circles/cycles? How is it possible to avoid the early breaking down of the current system, and all kinds of social risk associated with the departure of the current situation (e.g. unemployment)?

Managing transformations also requires the design of more integrative policies, i.e. research and innovation, agriculture, food, social and environmental policies. This need for integration is taken into account in various government tools, such as the Biodiversity Knowledge Center of the JRC, the European Green Deal, etc. Concerning health and the environment in Western Europe countries, the reader will find some illustrations of opportunities, challenges and gaps for greater policy integration and examples of good practices in White et al. (2020).

2.2.3. Production of actionable knowledge

To contribute to transformative changes that are generally systemic, the design and implementation of integrated iterative approaches are needed. Complementarity of lab research, design, demonstration and real-life experimentation have to be looked for in order to improve collective learning processes. Experimental activity should be conducted with research tools that are as much as possible representative of the real scale and "environmental" conditions. Experimental results should be validated with more comprehensive methodologies taking into account social and environmental impacts in addition to techno-economical aspects (Ngonghala et al. 2014).

Tackling complex challenges requires research to adopt an epistemology open to plurality and to design and to the implementation of interdisciplinary and transdisciplinary approaches (Hazard et al. 2020). Since they foster productive interactions of scientific knowledge, action knowledge and experiential knowledge, participatory approaches are relevant to this respect. Because they fuel a systemic look at the question at hand, they also help to identify and justify the relevance of scientific questions, with three types of possible benefits: it increases the legitimacy of research and change; it speeds up socio-technical transitions; it contributes to the deepening of citizenship and democracy.

Research on *ex post* research impact assessment shows that production of actionable knowledge is not just about providing knowledge on universal phenomena (Joly et al. 2015). *Ex post* analyses show that research that successfully contributes to socio-technical transformations generally contributes to the various steps of the impact pathway: production of knowledge and data related to specific local conditions, provision of technical objects (e.g., softwares, prototypes, new biological entities -plant varieties), technical or regulatory standards, new organizations. These various contributions of research are taken into account in the widely used scale "technology readiness level" (TRL) invented by NASA. However, against this linear representation, impact pathways are generally interactive. Productive interactions are one of the key engines of transformative research (Spaapen and Van Drooge 2011).

Whereas digital platforms that facilitate crowd-sourcing may ease the collection of data (e.g. for biodiversity observation) by non-(professional) scientists, this is only one form of participatory research. Coproduction is one of its key characteristics and it starts with the coformulation of research questions. The identification of users of the knowledge produced and of their place in research and innovation processes is a central question. It raises both pragmatic and political economy issues.

For knowledge institutions, managing the balance of excellence versus relevance is a central question. This raises institutional and organizational issues such as governance ones (whose voices count for the orientation and programing of research?) and quality control ones (e.g. from peer review to extended peer review).

Taking seriously the "local" level where socio-technical transitions take place requires to be much more attentive to local contexts, local initiatives and hence privilege bottom up processes. Funding (or research performing) agencies have to consider themselves no more as 'starting points' for projects/programmes, but rather as facilitators/modulators. This is real revolution of perspective for institutions that usually struggle for more visibility, legitimacy and power.

Importantly, a rising expectation (and support) to research also implies new responsibilities for researchers. This starts with the need that the "right" questions are identified and framed as mentioned above. This also implies to acknowledge that science and technology do not have all the answers and to challenge the technological fix attitude that is at the core of the culture of research organisations. Low tech and social innovations are indeed part of the solution.

In closing, the radical uncertainty and complexity we have to address challenge the current control syndrome which is pervasive in modern societies. This translates into a set of key tensions that were highlighted by the COVID-19 crisis: humility (not hubris); hope (not fear); diversity (not singularity); mutualism (not hierarchy); equality (not superiority or hegemony); precaution (not calculation); flourishing (not growth); and care (not control). Indeed, this requires cultural changes both within the scientific, administrative and political arenas.

3. International research cooperation delivering actionable knowledge on land and food systems in support of Agenda 2030

The way scientific institutions are organized has large implications for scientific knowledge integration across disciplines, across scales and across sectors. Integrated understanding of the nexus of SDGs requires novel ways to organize scientific communities and research programs. This applies especially to research on land-based systems, given the increasing demands placed on these systems to provide food, fibers, bioenergies and renewable energies, recovery of valuable products, to host cities and infrastructures, maintain rural communities and tourism, or for human health and well-being, while conserving natural resources and biodiversity.

To address global challenges and contribute to desired transformation, the previous sections have called for a necessary shift in knowledge production regimes. One of the major issues relates to the lock-ins within science communities themselves, when promoting sociotechnical pathways that prove to be unsustainable and generate path dependency. This is the reason why we will keep in mind the associated challenge to promote a public good orientation for research, when looking at the potential of international co-operation.

In this section, we consider the relevance of possible pathways to improve the international dimension in research in order to fuel actionable knowledge and science-policy interfaces, from local to global. We will first consider the role of international and multi-lateral cooperation and then look at conditions for strengthening it, both in conducting research and in interfacing science programming and delivery with policy decisions. We will finally suggest pathways to move forward.

3.1. International cooperation to strenghten science and science-policy interfaces

The 17 SDGs provide a political framework to tackle global challenges and SDG 17 calls for partnerships at all levels, in particular in the 70th paragraph of the 2030 Agenda for sustainable development for science and capacity building. When looking at complex challenges, international engagement and cooperation have become increasingly important for several reasons:

- The interdependency across countries and world regions has increased over the last decades by the rise in international trade and international travels, and globalization of supply chains, technologies and financial markets. Moreover, all countries are impacted by anthropogenic planetary changes and no single country, or world region, can tackle climate change, loss of biodiversity, land degradation, malnutrition and emerging infectious diseases in isolation.
- Scientific research increasingly involves international collaborations. About 75% of the research output of China, Brazil, India and South Korea remains entirely domestic, whereas international cooperation has strongly increased in Western Europe and now accounts for ca. half of the papers published (Adams et al. 2013).
- Literature shows (see Wagner et al., 2019) that internationally coauthored articles tend to be more highly cited than national coauthorships (Adams et al., 2013) or sole authored work (Glänzel and Schubert, 2001; Glänzel and De Lange, 2002); that the more elite the scholar, the more likely it is that they are working at the international level (Jones et al., 2008; Parker et al., 2010); and that international research tends to be more interdisciplinary (van Raan, 2003). However, there are multiple barriers to international collaboration, including lack of funding for international work, restrictions on material and data sharing, differences in academic standards and perceived bias against scholars from emerging or developing countries (Matthews et al., 2020).
- The opportunity for extending the impact of research investments across world regions by connecting complementary skills, knowledge and capacities through an articulated involvement of international multidisciplinary groups with diverse expertise and interests. This includes the facilitation of access to diverse skills, technologies, capabilities and facilities especially for scholars from countries with low investments in research and higher education.
- The need to produce global knowledge, norms, standards, conventions to shape the agenda, to frame the debate, to strengthen investments in research, and to address challenges at the global scale; this includes the importance to converge to coherent emerging outcomes, conserving the diversity of viewpoints, expertise (Finidori, 2016) and strengthening scientific communities in less advanced countries and poorly resourced regions.
- The interest for undertaking international comparative analysis to value the diversity of contexts, questions and pathways in order to design innovative answers. Noting that there are no mechanisms that will deliver integrative policies everywhere and for everybody (White et al. 2020), international partnerships are also important for designing answers and solutions at local and national level, with a specific interest from territories and local governments for adapted science-policy interfaces.
- The need to shape the scientific agenda for the next generation of researchers and to forge a conducive environment by acknowledging and promoting innovative and relevant international scientific programs and adapted science-policy interfaces.

Last but not least, an active international scientific cooperation supports multilateralism at a time where even the UN had to reaffirm that "our challenges are interconnected and can only be addressed through reinvigorated multilateralism" (Draft declaration on the commemoration of the seventy-fifth anniversary of the United Nations).

3.2. International research co-operation on land and food systems in support of Agenda 2030

To address more efficiently the Agenda 2030, revisiting international cooperation across research and higher education organizations will be pivotal. Developing (or low income) countries are often the ones most affected by land-based challenges, but have a low Human Development Index, which reduces their ability to respond to these interacting challenges (IPCC, 2019). Moereover, many developing countries are dwarfed in academic rankings. For instance, Africa is publishing less than 1% of world scientific publications. In the fields of agriculture, food and environment, all African countries are 7 times less cited than USA.

Such a strong imbalance questions how to further develop human capabilities, national science and technology capacity, and expertise in science policy in low income countries. Generic recommendations for international cooperation between developed and low income countries include: promoting co-ownership of the outcomes; applying and transferring results of joint research to local communities or industries and to society in general; evaluating the outcomes using appropriate methodologies and indicators; coordinating and harmonising programmes and projects (OECD, 2011).

International cooperation supporting the top-down strategic priorities of Agenda 2030 is even more difficult and questions the need for an orchestration at global level of science, technology and innovation (STI). Joint activities to support this orchestration could include benchmarking, researcher mobility and capacity building, joint research programming and implementation, advanced studies and foresights supporting science-policy interfaces. There are however a number of prerequisites for this to happen with successful outcomes.

Leading research organizations from contrasted world regions could agree on a shared vision concerning the main challenges for land and food systems and the role of science and technology to overcome these challenges. Such a shared vision could be derived, in part and despite gaps, from international expert assessment reports (see Part 1) concerning response options to interconnected challenges. An agenda of action could be based on a theory of change to address the SDGs both through institutional changes and through the promotion of a global orchestration of agricultural, food and environmental research. This could facilitate the development of joined research strategies owned by universities and institutes and supported by funding agencies, in order to implement actionable knowledge supporting transitions in the land sector.

A network, or alliance, of research organizations (including universities and institutes) could be initiated across world regions to address interlinked SDGs, their synergies and tradeoffs (see part 1) and to develop actionable knowledge supporting place based innovation (see part 2). This network, or alliance, would have the opportunity to support a new regime for global knowledge production, in particular through the acknowledgement and the promotion of e.g. transdisciplinarity, data sharing and transparency, integrated modeling across scales, open science and participatory research policies. Moreover, it could shape the next generation of long term international programs.

Bringing together complementary projects and expertise in a coherent way and shaping long-term international programs implies (1) coordination, (2) project alignment, (3) leverage of existing investments and intellectual property frameworks for core themes, and (4) the establishment of cohorts of international leaders through capacity building.

Portfolio management may become a powerful tool to bridge the gap between strategy and implementation by giving research organizations the possibility to better target complex challenges with higher probability of success. In some cases, it may lead to the creation of new research teams or partnerships (modelisation; visualization systems; interdisciplinary and interorganisational centers;….). When orchestrated by multiple organizations, this may generate a conducive framework to promote synergy and collaboration, rather than unnecessary redundancies and competition for resources that are usually scarce. However, we recognize that competition is part of the research process and is needed to stimulate high quality projects and publications.

Such an ambition, also requires revisiting institutional organizations and promoting reform of institutional management by moving from doing research for exclusive academic objectives to doing research as part of problem solving. Changing culture takes time, capacity building and the monitoring of research impacts.

To support such profound changes, adapted innovative funding mechanisms and cooperation across national or regional funding agencies are indispensable, also to ensure the involvement of research organizations from low income countries. In particular, this means escaping from short termism, which is usually the dimension most relevant for funding agencies, and planning for longer periods and multiple goals with the vision of a global orchestration of research and innovation supporting the SDGs.

3.3. Moving beyond obstacles toward a polycentric governance of global challenges

As noted by Sengers et al. (2020) for the governance of climate change: "a more voluntarist, bottom-up international governance approach emerged for the Paris Agreement in 2015", emphasising action by nation states, and innovation by business as well as non-state action. The expectation is that new actors will take "climate action" and develop practical ways of reducing emissions, filling the "governance gap".

This trend towards a polycentric and multi-actor governance can also be observed for biodiversity, with multiple alliances aiming at restoring landscapes, protecting rainforests, oceans, wildlife, etc. In the same way, a Land Degradation Neutrality Fund, or actions like the Great Green Wall are put in place to combat land degradation. Similarly, there are multiple initiatives for food security and nutrition (see e.g. GAIN, EAT foundation) that proactively advance the agenda on malnutrition and undernourishment. This polycentric governance allows far more possibilities to design science-policy interfaces, like expert panels created by scientific journals (e.g. the Lancet Commissions) often supported by foundations. Moreover, some initiatives include scientific and technical panels from the outset (e.g. the 4 per 1000 initiative, soils for climate and food security, Rumpel et al., 2020).

These trends are reflected in institutional changes, like:

- The emergence of processes under the auspices of UN conventions, such as the Koronivia process under the UNFCCC, which has seen workshops involving a dialog between climate change negotiators, funding agencies and observers, including scientists.
- Some UN bodies, such as the UN Committee for Food Security, have already an extended constituency including private sector, foundations, as well as civil society including NGOs and research.
- The emergence of Summits organized by the UN (such as the UN Food System Summit), or through inter-government processes (such as the One Planet Summits).

These new forms of international policy action can favor the role of research in designing and framing international initiatives on integrative responses to multiple challenges. This can be seen with recent examples: understanding the role of protected areas which are key for biodiversity, climate change and One Health issues; creating nature positive and climate neutral options through restoration of degraded ecosystems and of land, etc.

Designing appropriate arrangements for science-policy interfaces in this new context (approaches, effective tools and institutional set-ups including all relevant enablers of change, in particular foundations, development banks, investments funds, opinion makers groups and individuals) is also required. While science-policy interfaces are multiplying to address the plurality of problem, this also calls for the articulation among and between the relevant policy arenas they contribute to.

References

Adams J. (2013). The fourth age of research. *Nature*, 497, 557-560.

Agenda 2030. Transforming our World: the 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda

Albert, M. J. (2020). Beyond continuationism: climate change, economic growth, and the future of world (dis) order. *Cambridge Review of International Affairs,* 1-20.

Alston, Julian M., Jason M. Beddow, and Philip G. Pardey. 2009. Agricultural research, productivity, and food prices in the long run. Science 325 (5945): 1209–10. https://doi.org/10.1126/science.1170451.

Argyris C., (1993), Knowledge for Action, San Franciso: Jossey BassArnott, James C., Katharine J. Mach, and Gabrielle Wong-Parodi. "Editorial overview: The science of actionable knowledge." (2020): A1-A5. Current Opinion in Environmental Sustainability.

Barnosky, A., Hadly, E., Bascompte, J. *et al.* Approaching a state shift in Earth's biosphere. *Nature* 486, 52–58 (2012). https://doi.org/10.1038/nature11018

Barrett, Christopher B., Tim Benton, Jessica Fanzo, Mario Herrero, Rebecca J. Nelson, Elizabeth Bageant, Edward Buckler, Karen Cooper, Isabella Culotta, Shenggen Fan, Rikin Gandhi, Steven James, Mark Kahn, Laté Lawson-Lartego, Jiali Liu, Quinn Marshall, Daniel Mason-D'Croz, Alexander Mathys, Cynthia Mathys, Veronica Mazariegos-Anastassiou, Alesha (Black) Miller, Kamakhya Misra, Andrew G. Mude, Jianbo Shen, Lindiwe Majele Sibanda, Claire Song, Roy Steiner, Philip Thornton, and Stephen Wood. Socio-technical Innovation Bundles for Agri-food Systems Transformation, Report of the International Expert Panel on Innovations to Build Sustainable, Equitable, Inclusive Food Value Chains. Ithaca, NY, and London: Cornell Atkinson Center for Sustainability and Springer Nature, 2020.

Basso, B., & Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. *Nature Sustainability*, 3(4), 254-256.

Béné C., Fanzo J., Haddad L., Hawkes C., Caron P., Vermeulen S., Herrero M., Oosterveer P., 2020. Five priorities to operationalize the EAT–Lancet Commission report. Nature Food, VOL. 1, 457–459.

Breuer, A., Janetschek, H., & Malerba, D. (2019). Translating sustainable development goal (SDG) interdependencies into policy advice. *Sustainability*, 11(7), 2092.

Brundtland, G. (1987). Report of the World Commission on Environment and Development: Our Common Future. United Nations General Assembly document A/42/427.

Caron P., 2020. Confrontation des modèles : la coexistence pour naviguer entre naïveté du consensus et violence de la polarisation. In : Gasselin, P., Lardon, S., Cerdan, C., Loudiyi, S., & Sautier, D. (Eds.). (2020b, forthcoming). *Coexistence et confrontation des modèles agricoles et alimentaires : un nouveau paradigme du développement territorial ?* Versailles: Éditions Quae, pp 367-278.

Caron P., Ferrero y de Loma-Osorio G., Nabarro D., Hainzelin E., Guillou M., Andersen I., Arnold T., Astralaga M., Beukeboom M., Bickersteth S., Bwalya M., Caballero P., Campbell B.M., Divine N., Fan S., Frick M., Friis A., Gallagher M., Halkin J.P., Hanson C., Lasbennes F., Ribera T., Rockstrom J., Schuepbach M., Steer A., Tutwiler A., Verburg G. (2018). Food systems for sustainable development: Proposals for a profound four-part transformation. *Agronomy for Sustainable Development*, 38 (4): 12 p. https://doi.org/10.1007/s13593-018-0519-1

Collingridge, D. & Reeve, C. (1986) Science Speaks Truth to Power: The Role of Experts in Policy Making. Frances Pinter, London.

Crutzen, P. J. (2002, November). The "anthropocene". In *Journal de Physique IV (Proceedings)* (Vol. 12, No. 10, pp. 1-5). EDP sciences.

Den Boer ACL, Kok KPW, Gill M, Breda J, Cahill J, Callenius C, Caron P, Damianova Z, Gurinovic M, Lähteenmäki L, Lang T, Sonnino R, Verburg G, Westhoek H, Cesuroglu T, Regeer BJ, Broerse JEW, 2020.

Research and innovation as a catalyst for food system transformation. In: Trends in Food Science & Technology.

Desquilbet, M., Dorin, B. & Couvet, D. Land Sharing vs Land Sparing to Conserve Biodiversity: How Agricultural Markets Make the Difference. *Environ Model Assess* 22, 185–200 (2017). https://doi.org/10.1007/s10666-016-9531-5

Dorin, B., Le Cotty, T., 2014. Agribiom: A Tool for Scenario-Building and Hybrid Modelling, in Paillard, S., Treyer, S., Dorin, B. Agrimonde: Challenges for feeding the world in 2050, Springer and Quae, pp.9-36

Dorin, B., Joly, P.-B. 2020. Modelling world agriculture as a learning machine? From mainstream models to Agribiom 1.0. *Land Use Policy,* 96, 103624.

EAT Lancet (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems EAT Lancet (2019), *The Lancet*, Volume 393, Issue 10170, 2–8 February 2019, Pages 447-492.

Fanzo, J., 2018. Does Global Goal Setting Matter for Nutrition and Health?. *AMA journal of ethics*, 20(10), pp.979-986.

Farrell, J., McConnell, K. & Brulle, R. (2019). Evidence-based strategies to combat scientific misinformation. Nature Climate Change, 9, 191–195.

Finidori, H. (2016). Patterns that connect: exploring the potential of patterns and pattern languages in systemic interventions towards realizing sustainable futures. Proceedings of the 60th annual meeting of the international society for the systems sciences (isss), vol. 1 no. 1.

Foray, D., Mowery, D.C., Nelson, R.R. (2012). "Public R&D and social challenges: what lessons from mission R&D programs?" *Research Policy*, Vol.41, Issue 10, pp. 1697-1702.

Fuglie, K., Gautam, M., Goyal, A., Maloney,WF. (2020). Harvesting Prosperity: Technology and productivity growth in agriculture. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/32350

Gao, L., & Bryan, B. A. (2017). Finding pathways to national-scale land-sector sustainability. Nature, 544(7649), 217-222.

Geels, F., Sovacool, B.J., Schwanen, T., Sorrell, S. (2017) "Sociotechnical transitions for deep decarbonization", *Science*, Vol. 357, pp.1242-1244.

Glänzel, W., & Schubert, A. (2001). Double effort= double impact? A critical view at international co-authorship in chemistry. Scientometrics, 50(2), 199-214.

Glänzel, W., De Lange, C. (2002), A distributionalapproach to multinationality measures of international scientific collaboration, Scientometrics, 54: 75–89.

GSDR, 2019. The Global Sustainable Development Report "The Future is Now: Science for Achieving the Sustainable Development" (2019), United Nations.

Hazard, L. et al. (2020) "A tool for reflecting on research stances to support sustainability transitions", *Nature Sustainability,* https://doi.org/10.1038/s41893-019-0440-xHLPE. 2017. Nutrition and food systems.

Herrington, G. (2020). Update to limits to growth: Comparing the World3 model with empirical data. *Journal of Industrial Ecology.*

HLPE (2017) A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/a-i7846e.pdf

Hulme, M. (2020). One Earth, Many Futures, No Destination. *One Earth.*

IMF. World Economic Outlook, October 2020: A Long and Difficult Ascent.

IPBES (2020) Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services. Daszak, P., Amuasi, J., das Neves, C. G., Hayman, D., Kuiken, T., Roche, B., Zambrana-Torrelio, C., Buss, P., Dundarova, H., Feferholtz, Y., Földvári, G., Igbinosa, E., Junglen, S., Liu, Q., Suzan, G., Uhart, M., Wannous, C., Woolaston, K., Mosig Reidl, P., O'Brien, K., Pascual, U., Stoett, P., Li, H., Ngo, H. T., IPBES secretariat, Bonn, Germany, DOI:10.5281/zenodo.4147317.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

IPCC,2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

Joly, P.B., Gaunand, A., Colinet, L., Larédo, P., Lemarié, S., Matt, M. 2015. ASIRPA: A comprehensive theory-based approach to assessing the societal impacts of a research organization, Research Evaluation, 24 (4), 440-453.

Joly, P.B., Matt, M., Robinson, D. 2019. Research Impact Assessment: from ex post to real-time assessment, fteval JOURNAL, May 2019, Vol. 47, pp. 35-40

Jones, B. F., Wuchty, S., & Uzzi, B. (2008). Multi-university research teams: Shifting impact, geography, and stratification in science. Science,322(5905), 1259-1262.

JRC (2019). Mair, D., Smillie, L., La Placa, G., Schwendinger, F., Raykovska, M., Pasztor, Z. and Van Bavel, R., Understanding our Political Nature: How to put knowledge and reason at the heart of political decision-making, EUR 29783 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-08621-5 (online),978-92-76-08620-8 (print), doi:10.2760/374191 (online),10.2760/910822 (print), JRC117161 Report "Understanding our political nature. How to put knowledge and reason at the heart of political decision-aking" (JRC – 2019).

Kanger, L., Schot, J. (2019) Deep transitions: Theorizing the long-term patterns of socio-technical change, Environmental Innovation and Societal Transitions, Vol. 32, pp. 7-21.

Kharas H, McAthur J. The world is off track to end hunger, so what's the solution? Brookings Institute. Published October 23, 2017. Accessed April 19, 2018. https://www.brookings.edu/blog/future-development/2017/10/23/the-world-is-off-track-to-end-hunger-so-whats-the-solution.

Köhler, J., Geels, F. W., Kern, F., Markard, J.,…, Turnheim, B., Welch, D. & Wells, P. 2019. An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions,* 31, 1-32.

Kurian, M (2017) The water-energy-food nexus Trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environmental Science & Policy,* 68, 97-106.

Lamb WF et al. (2020). Discourses of climate delay. Global Sustainability 3, e17, 1–5. https://doi.org/10.1017/sus.2020.13

Le Quéré, C., Jackson, R.B., Jones, M.W. et al. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nat. Clim. Chang.* (2020). https://doi.org/10.1038/s41558-020-0797-x

Lenton T. et al, "Climate tipping points – too risky to bet against" (2019), Nature, 575.

Liu, J. Yang, W., Li, S. 2016. Framing ecosystem services in the telecoupled Anthropocene. Front. Ecol. Environ. 14, 27-36. https://doi.org/10.1002/16-0188.1R.

Mach, K., Carmen Lemos, M. et al. 2020. Actionable knowledge and the art of engagement, Current Opinion in Environmental Sustainability. 42, pp. 30-37.

Matt, M. *et al.* (2017) "Opening the black box of impact – Ideal-type impact pathways in a public agricultural research organization", *Research Policy,* 46(1). doi: 10.1016/j.respol.2016.09.016.

Matthews, K. R., Yang, E., Lewis, S. W., Vaidyanathan, B. R., & Gorman, M. (2020). International scientific collaborative activities and barriers to them in eight societies. *Accountability in Research*, 1-19.

Mazzucato M. (2018) "Mission-Oriented Research & Innovation in the European Union - A problem-solving approach to fuel innovation-led growth" *Governing Missions in the European Union"*, European Commission.

Miller, C., Wyborn, C. 2020. Co-production in global sustainability: Histories and theories, Environmental Science and Policy 113 (2020) 88–95.

National Intelligence Council, 2017; CIA 2035 prospective report Global Trend, Paradox of Progress. National Intelligence Council, January 2017, NIC 2017-001, Washington D.C. ISBN 978-0-16-093614-2.

Ngonghala CN, Plucinski MM, Murray MB, Farmer PE, Barrett CB et al. (2014). Poverty, Disease, and the Ecology of Complex Systems. PLoS Biology 12: e1001827. Doi: 10.1371/journal.pbio.10001827

OECD, 2011. OECD Global Science Forum. OECD Global Science ForumOpportunities, Challenges and Good Practices in International Research Cooperation between Developed and Developing CountriesOpportunities, Challenges and Good Practices in International Research Cooperation between Developed and Developing Countries, April 2 011

Parker, J. N., Lortie, C., & Allesina, S. (2010). Characterizing a scientific elite: the social characteristics of the most highly cited scientists in environmental science and ecology.Scientometrics,85(1), 129-143.

Lamy P. et al. (2017) "Investing in the European future we want - Report of the independent High Level Group on maximising the impact of EU Research & Innovation Programme", European Commission.

Pellegrini, P., & Fernández, R. J. (2018). Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. *Proceedings of the National Academy of Sciences*, 115(10), 2335-2340.

Pradhan, P., Costa, L., Rybski, D., Lucht, W., & Kropp, J. P. (2017). A systematic study of Sustainable Development Goal (SDG) interactions. *Earth's Future*, 5(11), 1169-1179.

Ramirez, M., Romero, O., Schot, J., & Arroyave, F. (2019). Mobilizing the Transformative Power of the Research System for Achieving the Sustainable Development Goals. SPRU Working Paper Series.

Raworth, K. (2017). A Doughnut for the Anthropocene: humanity's compass in the 21st century. The Lancet Planetary Health, 1(2), e48-e49.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., ... & Foley, J. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society*, 14(2).

Rumpel, C., Amiraslani, F., Chenu, C., Cardenas, M. G., Kaonga, M., Koutika, L. S., ... & Wollenberg, E. (2020). The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio*, 49(1), 350-360.

Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six transformations to achieve the sustainable development goals. *Nature Sustainabilit*y, 2(9), 805-814.

Schmidt-Traub, Guido, Michael Obersteiner, and Aline Mosnier. "Fix the broken food system in three steps." Nature (2019): 181-183.

Schot, J. and Steinmueller, W. E. (2018) 'Three frames for innovation policy: R&D, systems of innovation and transformative change', *Research Policy*. doi:10.1016/j.respol.2018.08.011.

Schwoob, M.H., Timmer, P., Andersson, M., Treyer, S. (2018) "Agricultural transformation pathways toward the SDGs", in Agriculture and Food Systems to 2050, Serraj, R., Pingali, P. (eds) World Scientific Series in Grand Public Policy Challenges of the 21st Century Vol 2, World Scientific, 680p.

Scoones, I., Dtirling, A. et al. 2020.Transformations to sustainability: combining structural, systemic and enabling approaches, Current Opinion in Environmental Sustainability. 42, pp. 65-75.

Sengers, F., Turnheim, B., & Berkhout, F. (2020). Beyond experiments: Embedding outcomes in climate governance. *Environment and Planning C: Politics and Space*, 2399654420953861.

SOFI (2017). FAO, IFAD, UNICEF, WFP, WHO. The State of Food Security and Nutrition in the World (SOFI) Report 2017

SOFI (2020). FAO, IFAD, UNICEF, WFP, WHO. The State of Food Security and Nutrition in the World (SOFI) Report 2020

Sonnino, R., Callenius, C., Lähteenmäki, L., Breda, J., Cahill, J., Caron, P., Damianova, Z., Gurinovic, M. A., Lang, T., Laperriere, A., Mango, C., Ryder, J. Verburg G., Achterbosch, T., den Boer, A.C.L., Kok, K.P.W., Regeer, B.J., Broerse, J. E. W., Cesuroglu, T., Gill, M. (2020). Research and Innovation Supporting the Farm to fork Strategy of the European Commission. Published by FIT4FOOD2030. Available through https://fit4food2030.eu/reports-publications/

Spaapen, J. M., & Van Drooge, L. (2011). Introducing 'productive interactions' in social assessment. *Research Evaluation*, 20/3: 211–8.

Stafford-Smith, M., Griggs, D., Gaffney, O., Ullah, F., Reyers, B., Kanie, N., ... & O'Connell, D. (2017). Integration: the key to implementing the Sustainable Development Goals. *Sustainability Scienc*e, 12(6), 911-919.

Steffen, W., Richardson, K., Rockström, J., Schellnhuber, H. J., Dube, O. P., Dutreuil, S. & Lubchenco, J. (2020). The emergence and evolution of Earth System Science. *Nature Reviews Earth & Environment*, 1(1), 54-63.

Stirling, A. (2010) "Keep it complex", *Nature*, Vol.468, pp.1029-1031

UNIDO, "Economics of Technological Lippfrogging", Inclusive and Sustainable Industrial Development Working Paper Series, WP 17 (2019).

Van Raan, A. F. (2003). The use of bibliometric analysis in research performance assessment and monitoring of interdisciplinary scientific developments.Technology Assessment-Theory and Practice,1(12), 20-2

Van Vuuren, D., Riahi, K., Calvin, K. V., Dellink, R., Emmerling, J., Fujimori, S., ... & O'Neill, B. (2017). The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Global Environmental Change*, 42 (PNNL-SA-120880).

Wagner, C. S., Whetsell, T. A., & Mukherjee, S. (2019). International research collaboration: Novelty, conventionality, and atypicality in knowledge recombination. *Research Policy*, 48(5), 1260-1270.

Weber, K. M. and Rohrracher, H. (2012) 'Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive "failures" framework', *Research Policy*. doi: 10.1016/j.respol.2011.10.015.

White P.C.L., Guégan J.-F., Keune H., De Bell S., Geijzendorffer I. R., Hermans C. M. L., Prieur-Richard A. H., Iroegbu C., Stone D., Vanwambeke S., de Vries S., Ford A. and Graham H. (2020). Integrative policy development for healthier people and ecosystems: a European case analysis. Area 52: 495-504. DOI: 10.1111/area.12618

French national research institute for agriculture, food & environment

RÉPUBLIQUE FRANÇAISE

Liberté
Égalité
Fraternité

INRAE