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# Transdisciplinary global change research: the co-creation of knowledge for sustainability☆

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The challenges formulated within the Future Earth framework set the orientation for research programmes in sustainability science for the next ten years. Scientific disciplines from natural and social science will collaborate both among each other and with relevant societal groups in order to define the important integrated research questions, and to explore together successful pathways towards global sustainability. Such collaboration will be based on transdisciplinarity and integrated research concepts. This paper analyses the relationship between scientific integration and transdisciplinarity, discusses the dimensions of integration of different knowledge and proposes a platform and a paradigm for research towards global sustainability that will be both designed and conducted in partnership between science and society. We argue that integration is an iterative process that involves reflection among all stakeholders. It consists of three stages: co-design, co-production and co-dissemination.

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## Introduction

Future Earth, a new 10-year international initiative on global sustainability research, was formally launched during the Rio+20 United Nations Conference on Sustainable Development in Rio de Janeiro, Brazil [1,2]. Future Earth (see also www.icsu.org/future-earth) will provide a new platform and paradigm for integrated global environmental change[a] research that will be designed and conducted in partnership with society to produce the knowledge necessary for societal transformations towards sustainability. Future Earth has been established and is supported by the 'Science and Technology Alliance for Global Sustainability' made up of ICSU, the International Social Science Council (ISSC), the Belmont Forum of global environmental change funding agencies, the United Nations Educational, Scientific and Cultural Organization (UNESCO), the United Nations University (UNU), the United Nations Environment Programme (UNEP), and the World Meteorological Organization (WMO) (currently as observer). This demonstrates the broad, global societal interest in, and recognition of the urgency and relevance of the topic. The Alliance also reflects agreement on the need and opportunity for moving global environmental change research towards new themes and approaches, as Future Earth is designed to do.

In this paper we first present the main research challenges of Future Earth and the need to further develop integrated research approaches. To achieve this three different dimensions of integration and their attributes are introduced. These are used to develop a comprehensive integrative framework. We thus aim to report on effective science integration and application processes to effectively address societal problems.

## Research challenges related to Future Earth

Future Earth is not some empty shell waiting to be filled. On the contrary, it builds upon decades of scientifically excellent research fostered by research programmes such as DIVERSITAS, IGBP, IHDP, WCRP and their scientific partnership, ESSP [20,52]. Furthermore, it is informed by the outcomes of several consultative, agenda-setting



[a] Global environmental change includes changes in the physical and biogeochemical environment, either caused naturally or influenced by human activities such as deforestation, fossil fuel consumption, urbanization, land reclamation, agricultural intensification, freshwater extraction, fisheries over-exploitation and waste production [20].

**Box 1 Research issues addressed in the development of Future Earth as formulated in [3•]:**

Grand challenges:

1. Forecasting — improve the usefulness of forecasts of future environmental conditions and their consequences for people.
2. Observing — develop, enhance and integrate the observation systems needed to manage global and regional environmental change.
3. Confining — determine how to anticipate, recognize, avoid and manage disruptive global environmental change.
4. Responding — determine what institutional, economic and behavioural changes can enable effective steps towards global sustainability.
5. Innovating — encourage innovation (coupled with sound mechanisms for evaluation) in developing technological, policy and social responses to achieve global sustainability.

Research challenge questions:

I. How can humanity feed a growing world population within sustainable boundaries of the Earth system? How can governance be aligned with the opportunities for global sustainability?

II. What risks is humanity taking in the Anthropocene, from negative implications on development to crossing tipping points with catastrophic implications for human societies?

III. How can the world economy and available technologies be transformed to stimulate innovation processes that foster sustainable development?

IV. In a rapidly urbanizing world, how can humanity design and sustain liveable and sustainable cities?

V. How can humanity succeed in a rapid global transition to a low-carbon economy that secures energy access for all and preserves the remaining biodiversity on Earth?

VI. How can societies adapt to the social and ecological consequences of warmer world, and what are the barriers, limits and opportunities in adaptation?

VII. How can natural capital, ecosystem services, and environmental processes on Earth be shared in a fair way among all citizens in the world?

VIII. What lifestyles, ethics and values are conducive to environmental stewardship and human wellbeing and how might these evolve to support a positive transition to global sustainability?

IX. How does global environmental change affect poverty and development, and how can the world eradicate poverty and create rewarding livelihoods while achieving global sustainability?

activities undertaken by members of the Alliance. Many of these activities have helped to raise awareness among the scientific community of new approaches to the organization, design and conduct of global change research, and have identified research challenges and related research questions that Future Earth should tackle (see Box 1). One such activity was the two-year ICSU-ISSC Earth System Visioning process, which resulted in a report 'Grand Challenges for Earth System Sciences for Global Sustainability' [3•], a second was the Transition Team[b] of Future Earth itself.

These challenges and research questions indicate that future research efforts need to focus more directly on producing knowledge required to understand and diagnose the challenges that confront societies as a result of global change.[c] The need for further scientific evidence should be guided by these societal challenges. In addition, the transition towards the sustainable use of the Earth's resources can only be reached through deliberate processes of transformation [4] which have to be managed creatively by societies on the basis of sound scientific knowledge.

The knowledge that should be produced through research activities to meet the research challenges formulated in Box 1 is obviously not only defined by the knowledge gaps as perceived by single scientific disciplines, but also by the priority which societies place on the sustainability challenge. It calls for new research strategies, with a strong focus on joint efforts by researchers from the natural, social and human sciences and engineering to contribute to the co-design of a global sustainable future.

At first glance it looks as if this new research strategy may convert global change research from primarily a science enterprise into an applied and even transdisciplinary (i.e. driven by stakeholders' needs) research endeavor[d] like energy system research, research on sustainable production systems, mobility research, or

[b] The Transition Team, a committee that is leading the initial design phase of the Future Earth initiative, is comprised of seventeen members from a wide range of disciplines and countries, and also includes ex-officio members representing the main partners of the Science and Technology Alliance for Global Sustainability.

[c] The analysis in the paper does not focus solely on global environmental change, but on a broader range of global problems. Many of these are unrelated to environmental change; they have significant consequences for society but do not necessarily involve changes in the Earth system. Yet environmental change can aggravate such problems, and in some cases is already doing so. It is the complex interplay of environmental change, its global impacts and its embeddedness in social systems, that serve as the focal domain of the paper — and this is referred to simply as 'global change' in the rest of this paper.

[d] Hirsch Hadorn *et al.* [10] for instance distinguish between basic science, applied science and transdisciplinary science. Today also terms such as solution-oriented research [2,11] or actionable science [8,12] are used to describe this problem oriented branch of science in more detail.

research on food water and energy security. In applied and transdisciplinary research major questions are derived from societal needs whenever their established set of scientific methodologies will need to be supplemented by newly structured and prioritized approaches and processes. Their research results should assist societies to make informed decisions. Does this model of applied research also hold true for the research that is necessary in the context of Future Earth? If yes then for the upcoming decade researchers will face a clear shift from a business-as-usual basic science to transdisciplinary research approaches where — in addition to collaboration and integration across scientific fields — research questions no longer emerge from science alone but in interaction with civil society, governments and other stakeholders.

## Integration of knowledge as a new challenge in Future Earth

The differentiation, specialization and fragmentation of science into disciplines over the last centuries have gone hand in hand with extraordinary progress both in the quantity and quality of knowledge produced. The accompanying self-dynamics of scientific progress with the division of labour and the emerging incentive systems strongly supported the trend for individual scientists or groups of scientists to invent their own languages, journals, career systems and curricula [5], and eventually to tailor their research questions according to their ability to cope with their own cultural, technological and/or organizational structures. Consequently, specifically tailored (discipline-based) scientific questions often do not address the grand societal challenges and are therefore of inadequate scope and scale for the challenges of Future Earth. On the one hand disciplines are good at providing essential knowledge, methods and tools [6]. On the other hand, disciplinary approaches tend not to have the capability to handle complex challenges (e.g. climate change, public health, food and water insecurity) that demand cross-disciplinary collaboration [7]. As a result, researchers within their scientific disciplines usually cannot adequately approach these grand research challenges of sustainability despite their being of outstanding importance to the society in which they live (and, if they start addressing these challenges, they will be 'disciplined' by their peers).

A central tenet of integrated research is researchers working on problems and in contexts of application and not in disciplines, stimulating discoveries and interactions between fields [8,9]. There are many examples in the past where failure to integrate on the one hand resulted in inadequate knowledge [53], while integration of different fields of knowledge resulted in valuable contributions of science to societal problems [54]. For instance, eighteenth and nineteenth century botanists and chemists in Europe were not able to solve the prevailing societal and scientific challenge of conquering hunger. Only the introduction of agricultural universities across Europe during the second half of the nineteenth century provided the necessary organizational, technological and cultural platforms for science to tackle a grand societal research challenge — the prevalence of hunger in Europe — by integrating knowledge that was formerly too spread out among the disciplines to be utilized by a small group of specialized scientists. Besides innovative research, this also required excellent extension services and other links to societal needs.

The integration of research from different disciplines gathered traction during World War II because of the need for problem-focused, cross-disciplinary research to achieve political and military ends [13]. The Manhattan Project and the early US Space Programme are considered informative examples of integrated research [9,14,15]. The impetus for integrated research continued over several decades after the war with the creation of new laboratories and institutes in nuclear science, radiology, biophysics, marine physics and atomic research [16,9]. Additional examples include Watson and Crick's discovery of the structure of DNA and its aftermath (benefitting from biology and physics) and the amalgamation of disciplines such as neurobiology, psychology and computer science which all led to the creation of cognitive sciences [14]. These examples demonstrate the successes of integrated problem-oriented science (particularly collaborative research between natural sciences) but they can also demonstrate that societies or their parts have to play a more active role in the definition of research foci and topics and in collaboration with science.

Recognition of Earth as an integrated system [17,18,7] drew attention to the need to integrate approaches from different disciplines to tackle scientific questions about the complex processes making up the Earth system. Examples include the quantification of the Antarctic ozone hole by atmospheric chemists and meteorologists and an improved understanding of the causes and consequences of acid rain through collaboration between atmospheric scientists and terrestrial ecologists [19,20]. At the same time, many results of integrated research provide important information for decision makers in society. For example, the 'Climate Change, Agriculture and Food Security' programme's 'Integration for Decision Making' research project provides an analytical and diagnostic framework, that is grounded in the policy environment, incorporates biophysical effects, quantifies uncertainty where possible, and ensures effective engagement of rural communities and institutional and policy stakeholders (see: ccafs.cgiar.org/our-work/research-themes/integration-decision-making). Integrated global change research results also form the basis of high-impact international science-policy assessments such as the 'Millennium Ecosystem Assessment', the 'Intergovernmental Panel on Climate Change', 'The Economics of Ecosystems and Biodiversity' and the recently established 'Intergovernmental Platform on Biodiversity and Ecosystem Services'. These assessments predominantly rely on integrated research efforts and also serve societal needs (e.g. through their summaries for policy makers).

## The knowledge production process

It appears self-evident that integration is essential when looking at Future Earth's research challenges. However, it seems equally clear that integration has to work against the gravity of established organizational, technological and cultural structures of today's science. In addition, integration across scientific disciplines has to consider the multiplicity of worldviews present in contemporary science [21•]: the reductionist and contextual views. In the reductionist view, gaining knowledge is achieved by focusing *only* on understanding the parts of the system. It is thus not useful to look at the interfaces and complex coupling between the entire system's components to understand the function and effect of the sum of its parts [22]. This worldview resulted in the extremely successful analytical approaches throughout science, and is largely the basis for the technological progress during the last centuries, for example, in pharmaceutical research, solid-state physics or genetics. Knowledge should — in the reductionists view — ultimately be put in a formal framework and thus be universally recognizable and to a large extent exchangeable across contexts. The focus is not on the preservation of the quality and diversity of knowledge, but on the flow and exchange of knowledge between agents, particularly between those embedded in the same scientific culture. Under this worldview, a general goal of integration would be to create interfaces between the scientific cultures and their languages, which would allow exchange and co-utilization of disciplinary knowledge.

An opposing worldview considers knowledge as being composed of different configurations and validated practices that emerge as a result of agents' learning within their natural and/or societal contexts. Thus knowledge is mostly what works in a particular context. Consequently, what is learned need not be transformed into a formal representation by using a specifically designed language; such a reduction would destroy the contextual meaning of the knowledge. In this worldview both social and natural science knowledge are interdependent and inseparable aspects of the same knowledge. The robustness of knowledge is validated by checking its impact on the considered socio-natural system of reference [23]. Under this worldview, a general goal of integration would be to protect, promote, and whenever possible, incorporate the diversity of languages and forms of knowledge in ways that become relevant for sustainability in particular contexts of application.

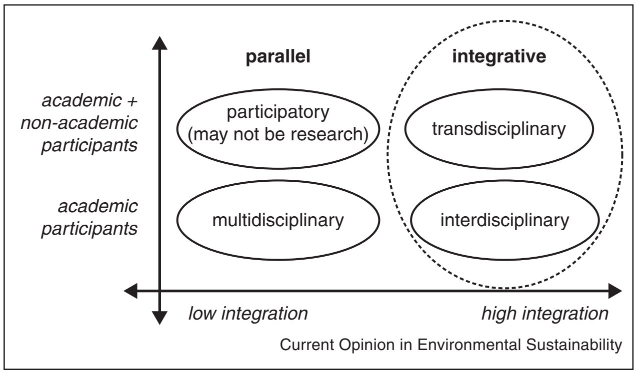
It seems clear that these two worldviews have very different implications with regard to integration during the process of knowledge production. In the Future Earth context this means that in essence integrated research requires a process that brings together the different worldviews with the aim of benefitting from both approaches. The predominantly reductionist approaches in the natural sciences need to be combined with the more contextual approaches of many social science methods. Any research activity addressing societal problems is likely to require a combination of reductionist theorizing and analysis with a reflection of the societal contexts in which the research is located. Finally, in societally relevant research, the gap between science as the active knowledge producer and society as the passive recipient in the knowledge production process will need to be replaced by a process of co-design and co-production of knowledge.

## Concepts of integration

Since everyone is free to define/refine research concepts, a plurality of integration concepts can be found in the literature. Transdisciplinarity, interdisciplinarity, multidisciplinarity, pluridisciplinary, crossdisciplinary and their mutual relationships, as well as their impact on how to actually do research, have been issues of intensive debate in general science and education [6,15,23–25,26•,27,28,29••,30] as well as in research on global change and sustainability [10,31–33,34••,35,36•]. As a consequence, there does not exist a common language for defining the different approaches, and this leads to many misunderstandings and barriers to communication [25].

According to Tress *et al.* [25] the strength of integration varies across research concepts, from low (participatory, multidisciplinary) to fully integrated (interdisciplinary, transdisciplinary). Much of the literature stresses that transdisciplinarity, in comparison to interdisciplinarity, is also characterized by the involvement of non-academic actors in the research process (see Figure 1). Nicolescu [37] explains that the prefix 'trans' indicates '...[working] between the disciplines, across the different disciplines, and beyond all disciplines'. And Lang *et al.* [36•] defines transdisciplinarity as a reflexive principle '...aiming at the solution or transition of societal problems...by differentiating and integrating knowledge from various scientific and societal bodies of knowledge'. But as mentioned above, the views of experts are variable (mostly in detail). In this paper it is not our aim to discuss the numerous different views/definitions from a theoretical perspective. Instead, for understanding the ongoing academic discussion we would like to review briefly the positions of two experts from different communities on the subject of transdisciplinarity.

**Figure 1**




Degrees of integration and stakeholder involvement in integrative and non-integrative approaches according to Tress et al. (2005) with kind permission from Springer Science+Business Media.

Attempts to fill transdisciplinarity with content date as far back as the 1970s when Erich Jantsch postulated that innovations in planning for society at large in a government–industry–university triangle should include a far-reaching re-organization of higher education into an education–innovation system, because 'the classical single-track and sequential problem solving approach itself becomes meaningless today' [24]. Jantsch put forward the idea that knowledge creation should be organized and coordinated in hierarchical systems at four levels: purposive (meaning values), normative (social systems design), pragmatic (physical technology, natural ecology, social ecology) and empirical (physical inanimate world, physical animate world, human psychological world). This top-down coordination should follow horizontal principles within each level and vertical principles between levels and sub-levels. Transdisciplinarity, according to Jantsch, is reached at the ultimate level of coordination since 'the essential characteristic of a transdisciplinary approach is the coordination of activities at all levels of the education/innovation system towards a common purpose.' [24]. Mittelstrass [29••,38] has a more pragmatic and evolutionary view on transdisciplinarity when he contests that 'scientific cooperation in general means readiness to engage in cooperation in science, and interdisciplinarity normally means concrete cooperation with a finite duration, transdisciplinarity is intended to imply that cooperation will lead to an enduring and systematic scientific order that will change the outlook of subject matters and disciplines.' Transdisciplinarity in this context is 'a principle of research and science, one which becomes operative wherever it is impossible to define or attempt to solve problems within the boundaries of subjects or disciplines, or where one goes beyond such definitions'. It is consequently seen as a natural step in the development of scientific collaboration. For Mittelstrass it is nevertheless useful to distinguish between practical transdisciplinarity where science addresses sets of problems not intrinsic to science and theoretical transdisciplinarity that originates from more strictly scientific sets of problems.

He views for example ecological research as of the practical transdiscplinarity type. For him to solve scientific ecological problems collaboration and a 'wise and efficient coordination' of a broad range of disciplines from natural science and humanities is necessary, 'but not an extension or transformation of these disciplines'. Research on global change and sustainability in this sense is also of practical transdisciplinarity. It requires the collaboration of many disciplines, for instance physics, chemistry, biology, geography, sociology, psychology, economics, law, and/or ethics. They contribute with their specialized knowledge to the solution of these problems, 'and a wise and efficient coordination, but not an extension or transformation of these disciplines, is required' [29••].

In both positions an overall need for coordination is seen as an integral part of transdisciplinarity. The difference in these two positions lies within the assumed nature of research coordination as a more top-down or bottom-up process. Although not mentioned by either author, it is the integration of the disciplinary contributions that is at the heart of transdisciplinarity, and which gives transdisciplinary coordination a direction. Mittelstrass [29••] claims in contrast to Jantsch [24] that transdisciplinarity is not trans-scientific; it retains subjects and disciplines, which have been constituted historically, and is solely meant to overcome the boundaries between them.

## From theory to practice

Since the debate about different research approaches is still going on in science, there is no final conclusion about a 'correct' way to coordinate the sciences in an integrated or transdisciplinary manner. Nevertheless, the grand challenges of sustainability demand the development of pragmatic approaches to the integration and conduct of transdisciplinary research.

For integrated research to meet the needs of users more effectively, as well as to inform sustainable policy directions, it is therefore necessary to establish what integration means in a practical Future Earth context. This opens up several questions related to Future Earth: 'Will research undertaken within the framework of Future Earth be any different from what we commonly understand as being applied research?', 'Why should sustainability science not be considered just another branch of engineering?', 'What are the specific challenges for science with respect to the interactions between science and society that the Future Earth principles of co-design and co-production of knowledge emphasise?'.

The aforementioned theoretical discussions on what transdisciplinary coordination and integration mean for practical research within Future Earth were condensed to the following key question:

'How would a new platform and paradigm for global change research look like, that will both be designed and conducted in partnership of science with society to produce the knowledge necessary for the societal transformation towards global sustainability?'

This formed the basis for the German National Committee on Global Change Research (NKGCF, www.nkgcf.org) to initiate, in cooperation with ESSP, ISSC and ICSU, a workshop on 'Integrated Global Change Research: Co-Designing Knowledge across Scientific Fields, National Borders, and User Groups'. The workshop was held on 7–9 March 2012 at the Berlin-Brandenburg Academy of Sciences (Berlin, Germany) and was sponsored by the German Research Foundation (DFG). The focus of the workshop – in which over 50 senior and mid-career scientists with long-term interdisciplinary and transdisciplinary experience, as well as stakeholders from different parts of the world participated – was to discuss and evaluate current examples of integrated research, to debate the notion of integration across different fields, national boundaries and user groups as a basis for the co-design of knowledge, and to identify the key components of efforts to take forward the successful co-design and co-production of knowledge of relevance to Future Earth. Building on workshop participants' insights, this paper illuminates useful processes of integration and describes the main practical challenges to, and opportunities of, the integration of knowledge.

## The shift from business-as-usual science to a new research model in global sustainability

The societal challenges given in Future Earth (c.f. Box 1) describe problems where the need to move from disciplinary approaches to integrated (interdisciplinary and transdisciplinary) approaches is both necessary and evident. According to Lang *et al.* [36•], key arguments for moving to such new types of research collaboration are:

- Research on complex sustainability problems requires input from various communities of knowledge (e.g. science, business and government). Since it is not clear from the beginning what knowledge from different disciplines and actor groups will be relevant in a given context, an open, integrated process involving insights from many potential actors is required;
- Solution-oriented research requires knowledge production beyond problem analysis and the provision of system understanding. Goals, norms and visions need to be included, as they provide guidance for transition and intervention strategies[e];
- Collaborative efforts between researchers and non-academic stakeholders promise to increase legitimacy, ownership and accountability for the problem, as well as for the solution options.

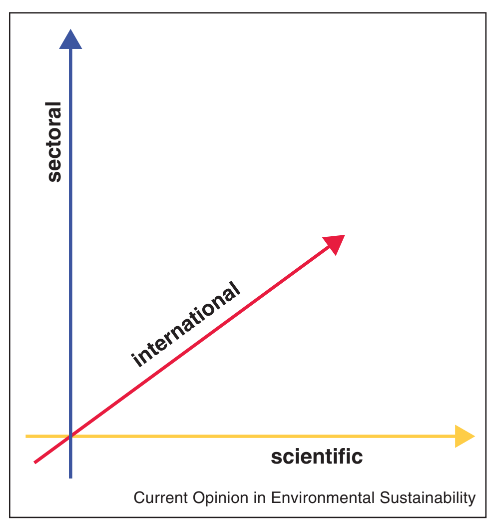
[e] This is an example where the reductionist and contextual approaches to scientific inquiry need to come together.

Despite sustained pleas for integrated research in global change and sustainability science [18,39–43], integrated approaches have yet to be implemented in environmental science to the extent that Jantsch [24] or Mittelstrass [29••,38] have proposed. We therefore considered it worthwhile to examine more closely integration and transdisciplinarity, which is a key element of integration. We also support the understanding that transdisciplinarity is a reflexive learning process that goes beyond interdisciplinary research and involves academics and non-academics (e.g. stakeholders, decision makers of policy, society and economy). This follows the view of several other authors, for example [10,25,36•,37,44].

From the practical perspective of what integration could be, we suggest — based on the discussions in the workshop — to distinguish between three different dimensions of integration (see Figure 2):

(a) *Scientific dimension of integration*: This addresses the integration of knowledge, concepts and methods from different scientific disciplines. Case studies of different approaches towards scientific integration (e.g. food systems, water security, climate change and land management) were presented and discussed,

**Figure 2**




The transdisciplinary Future Earth integration space as seen by the Berlin workshop (March 2012); *scientific integration* = integration across academic and social sciences, humanities and engineering) disciplines, *international integration* = integration from local to global and across nations and cultures and *sectoral integration* = integration across science and society.

along with experiences gathered from integrated research projects [45–50]. Workshop participants indicated that scientific integration can either be organized by: (I) developing a common mission, (II) developing a common conceptual framework and language, (III) considering cross-cutting issues, or (IV) combining methodological approaches. Integration can operate at least in three different modes: additive (e.g. a cost benefit analysis of a certain climate policy option), combinatory (e.g. representative climate projections and socio-economic scenarios), or systemic (e.g. Earth system models with complex feedbacks).

Regarding coordination of scientific integration, four points were identified, which need to be addressed in a systematic manner:

i. How to integrate across scientific disciplines in a consistent way? The three modes of scientific integration do not ensure that the integrated entities fit in their data, assumptions and understanding, and that comparing apples with pears is avoided. There is a general lack of systemic approaches that are designed to identify inconsistencies in integration. And there is a lack of communication among representatives of the different approaches.
ii. Scientific integration versus scientific autonomy of disciplinary research. Research results from participating disciplines form the basis on which to integrate. To what extent do the interdependencies established through integration between the participating disciplines dictate their research topics and how can the two worlds (i.e. integrated and specialist) co-exist?
iii. How can the necessary critical reflexivity on boundaries of science and knowledge be organized between disciplines? Integration creates interfaces between the participating disciplines and with the outside, non-scientific world. The criteria of where and how and with which contents to establish these interfaces is still an open question.
iv. How can we develop new concepts, processes and common scientific languages? The case studies demonstrate the importance of communication between the participating scientific disciplines and stakeholders for successful integration. It is not yet clear which concepts and processes are most suitable to support communication and what the properties of integration languages should be.

(b) *International dimension of integration*: This dimension addresses the world-wide character that international research initiatives like Future Earth seek to promote, the local-national-regional character of sustainable solutions and the need to include all relevant knowledge from epistemic communities across countries, regions, cultures and societies.

Sustainable development and global change are common scientific challenges that bring together people with very different values and worldviews to cooperate in research [51]. The exploration of suitable institutional, economic and behavioural changes towards global sustainability will lead to solutions that are highly dependent on, and tailored to, local, national and regional cultural, economic and natural contexts. Integration of research questions, from the local to the global and back, means considering the other scales when carrying out research on the one scale (be it local, national, regional or global). This ensures that differences in cultures, interdependencies between regions and institutional dependencies are adequately (i.e. in an equitable fashion) taken into account.

Regarding international integration five critical points have been identified by the workshop participants:

i. How to best solve the problem of fit? International integration should fit the scale of the social–ecological problem and challenge to be addressed. The region and scale for international research integration (local–national–regional–global) should depend on the problem to be addressed.
ii. How to ensure that basic research principles and standards are met?
a. The universality principle: people should have a right to have equal access and means to agenda setting, data, methodologies and results.
b. Universal standards of quality of science (e.g. transparency, replicability, excellence and data quality) while respecting the possibility to frame the problems to be addressed differently and bringing different conceptual and methodological tools to bear on those problems.
c. Diversity in the research and knowledge systems and language should be preserved and respected.
iii. How to reduce the strong asymmetries in research capacities, money and power among the international partners from the developing and developed worlds?
iv. How to identify best solutions from different regions through the benchmarking of best practices; how to exchange, replicate, adapt and integrate methodologies of research developed under different national/regional contexts?
v. How to best integrate for collection and common use of environmental and societal data from different regions of the World?

(c) *Sectoral dimension of integration*: This dimension addresses the co-design and co-production of knowledge between actors from the state, knowledge institutions, market and civil society sectors so as to achieve a mutual understanding of the kinds of research questions that need to be addressed and the ways of doing so. The purpose of sectoral integration is to ensure that, through joint, reciprocal framing, design, execution and application of research, science and societies approach the transformations towards sustainability in a structured and knowledge-driven way. The integration of stakeholders and decision makers, who were formerly distant to the process of scientific agenda-setting and knowledge creation into these processes, both enhances mutual understanding and mutual responsibility. No definitive blueprint exists yet for this dimension of integration; it comprises new forms of learning and problem-solving action of different parts of society and academia that have not traditionally been in close contact.

Regarding sectoral integration, three critical aspects were identified by the workshop participants:

i. How can communication between the different actors from state, knowledge institutions, market and civil society sectors be best organized to become effective? The common difficulty of communication among scientists from different disciplines takes on a further dimension when it is joined by discussion on the same topic with stakeholders from different societal sectors. Therefore, it is not clear how to embed such discussions and how to establish a common knowledge platform for the partners.

ii. How to define sectors and relevant actors in each context according to the research issue identified? No mechanisms are available to decide in a non-exclusive way which sector should participate in the definition and solution of a research issue.

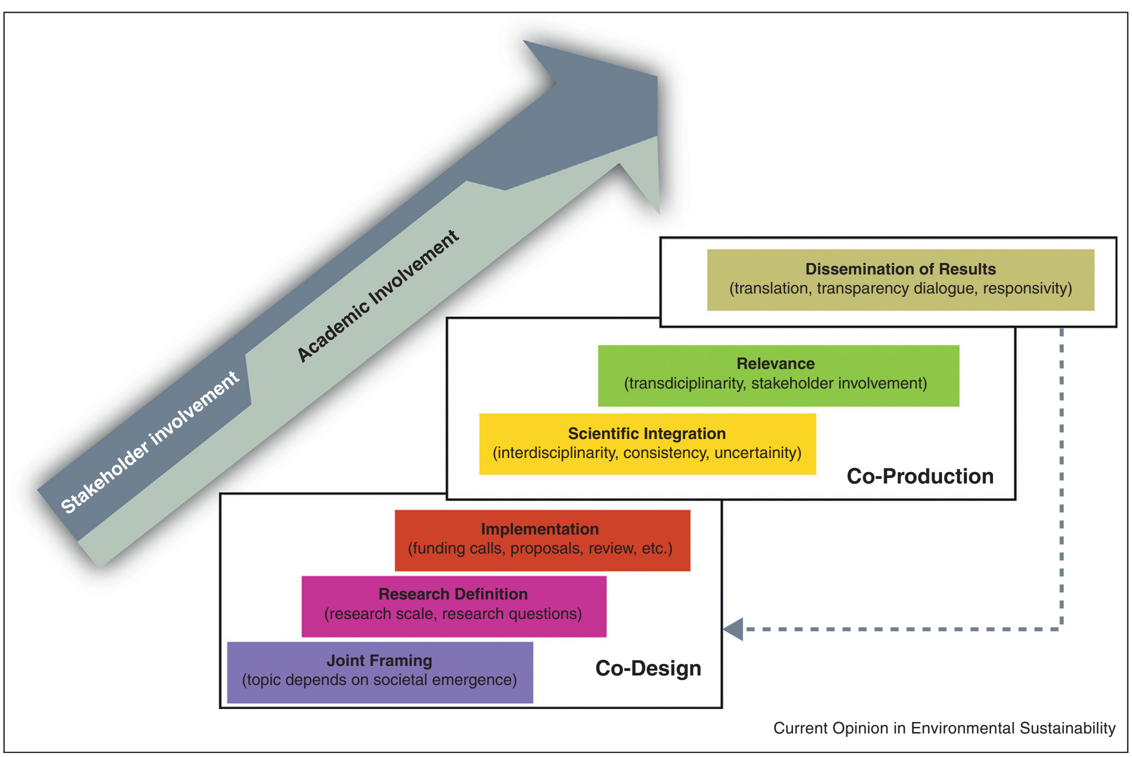
iii. How to best translate results from research into knowledge that is useful to society, and how to best translate societal needs for knowledge into science questions and operational research programmes? A number of initiatives have been started or are in the process of design, such as the Climate Service Center (CSC) in Germany (www.climate-service-center.de) or the climate services envisaged by the WCRP (www.wcrp-climate.org). It will remain to be seen whether these attempts will be capable of providing an appropriate platform for fruitful, integrated communication between science and society.

All three dimensions need to be realized if a successful transdisciplinary global change research system is to be implemented. Furthermore, these three dimensions of integration build the basis for the proposed model of co-creation of knowledge within the Future Earth process.

## Co-creation of knowledge

We propose a framework for integration (Figure 3) within the Future Earth context. The process of co-creation of knowledge — as it was developed during the workshop — consists of three fundamental steps throughout which both academia and stakeholders are involved to

**Figure 3**




Framework for interdisciplinary and transdisciplinary co-creation of the knowledge castle.

varying degrees: co-design, co-production and co-dissemination. During these consecutive steps the three dimensions of integration are of varying importance to the overall knowledge creation process.

It starts with the *co-design of the research* agenda through sectoral integration between stakeholders and decision makers from the relevant societal sectors and science to develop a viable research issue to the point at which it can be handed over to the broader scientific community. The process of co-design starts with the joint framing of sustainability challenges faced by society. The next step concerns the translation of the sustainability challenge into a definition of the required knowledge that needs to be offered through research. Important issues are the scale, both spatial and temporal, of the required research and the necessary depth of international and scientific integration. In the process of research definition, the research questions are portioned into manageable research projects. This step leads to research management procedures like research funding calls, proposals and reviews, which are either well established or which have to be tailored to the specific integrated project by the funding agencies. During the co-design phase stakeholders and academic participants work in a coordinated, integrated way to best establish a common understanding of the research goals, to identify the relevant disciplines, participants and the scientific integration steps necessary to approach the topic, and to agree on the roles the different groups have in advancing towards the research goals.

The second *step* consists of the *co-production of knowledge*. Here, the transdisciplinary focus is on scientific integration. During this phase integrated research is conducted as a continuous exchange among the participating scientists and with the stakeholders. Scientific integration takes care of proper interdisciplinary approaches and interfaces, which ensure consistency of the research process across the participating disciplines and also deal with questions of the uncertainty of the results. Scientific integration also ensures that the necessary disciplinary research questions are derived from the overall needs of the project and then researched by the respective discipline, and that the scientific quality is maintained in the research process. Finally, dialogue between stakeholders and scientists ensures the exchange and interaction of their respective knowledge and thereby ensures the societal relevance of the research

The last step consists of the co-*dissemination of the results* among the different societal groups. This includes publication of the acquired knowledge also in accessible language, translation of the results into comprehensible and usable information for the different stakeholders, and an open discussion on the valuation, applicability and relevance of the results among groups of conflicting interests. This open discussion of the results and the consequential actions taken by society towards reaching the goal of sustainability leads to new research questions, which will then jointly be framed, which initiates a new transdisciplinary research cycle. Figure 3 demonstrates that integration is an iterative process that involves ongoing reflection among all participants.

## Conclusions and the way forward

Carrying out research that will fulfil the ambitions of Future Earth means committing to do science together with society: in other words, to commit to transdisciplinary and thus integrated processes of co-designing research agendas and to co-producing knowledge with researchers, decision makers and stakeholders for addressing challenges for global sustainability and developing possible solutions. Integrated research provides a better understanding of the multiple drivers, interdependencies and complexities of global sustainability challenges. It provides knowledge that is better able to contribute to the development of robust policy solutions and their effective, equitable implementation.

Integrated research works across scientific disciplines, across regions and across societal groups. It is problem-oriented, driven by contexts of application, and starts with the joint framing of research topics and questions. It requires the involvement of researchers, stakeholders and decision makers throughout the entire research process, from co-design through co-production to effective delivery, and thus demands clarity about the roles and responsibilities of those involved.

Integration upholds scientific integrity in reflexive learning processes that bring together different actors and knowledge practices. It builds on, and supplements, traditional processes of disciplinary research.

Co-production of knowledge in global change research changes the way research is done and needs new methods and concepts. It requires appropriate communication tools, institutional arrangements, and tailored funding possibilities. In this it can draw on other experiences, such as those mentioned earlier (e.g. the Manhattan Project and CCAFS).

Successful integration calls for critical reflection at all levels — among researchers, funders, and science policy makers — on the role of science in global sustainability, and on the practices of research and research management that will be needed to make this new type of relationship between science and society come to life.

We tackled the question of integration of knowledge and to begin a process of reaching a new international consensus on, and commitment to, integrated sustainability research. From the science perspective, involving funders and science policy makers presents challenges as well as great opportunities for providing the necessary institutional framework. The challenges, that must be met, involve:

- **Develop new processes and skills:** Integration requires strong process-oriented skills (inter-personal, communication and facilitation), as well as organizational and managerial competencies, that are not always available and may require professional support or training. Educational institutions as well as funding agencies will play an important role in this.
- **Deal with inertia to change:** Integration also requires critical reflection on the role of science in global sustainability and on the limitations of doing business-as-usual research. This, in turn, requires an openness to change. Neither process is necessarily easy or comfortable for those involved.
- **Clarify roles, responsibilities and rules of engagement:** Integration is research coordination, which spans the entire research process. Different actors will have different levels and forms of involvement in different parts of the process. This requires clarity about roles and responsibilities, about who makes decisions when, and about how to appropriately safeguard scientific integrity and relevant standards of quality.
- **Establish integrated institutions:** The disciplinary-based practices and structures of existing educational and research systems are not conducive to integrated efforts, and will need to be supplemented with new, integrated structures.
- **Develop support systems:** The same is true for typical academic reward and career advancement systems, as well funding mechanisms — including selection and evaluation procedures. Integration calls for a critical review of such systems.
- **Remove persistent inequalities:** In terms of access to power and resources, as well as research capacities, the world of science is plagued by persistent inequalities that pose a fundamental challenge to the deeper levels of collaboration that integration calls for.

To adequately approach these challenges of co-design, co-production and co-dissemination of knowledge, the following requirements are necessary from the outset:

(i) the design and implementation of new support and management structures,
(ii) the development of a diversity of skills for managing integration processes, including the necessary reward structures, and
(iii) adjustments to funding mechanisms, including selection and evaluation procedures.

Future Earth provides major opportunities for advanced sustainability research by providing both the necessary international institutional structure and the platform for defining a research agenda for the next decade of research. The Berlin Workshop has clearly shown that the challenge of integrated research requires a focus on a number of additional aspects. Integration will not happen by itself but needs active support and organizational adjustments in the research process. Future Earth is now in a unique and powerful position to: firstly, promote critical reflection on what kind of science we want for what kind of world; secondly, provide a platform for discussions about the implications of promoting the co-design and co-production of knowledge for global sustainability; thirdly, suggest the introduction of appropriate research management processes and structures, as well as funding modalities and other support systems, to make integrated research across scientific fields, national borders and user groups a reality; and fourthly, work with members of the International Science and Technology Alliance for Global Sustainability that established Future Earth to build a sound, practical understanding of Future Earth processes in broader systems of research at national, regional and international levels.

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