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Responding to complex societal challenges: A decade of Earth System Science Partnership (ESSP) interdisciplinary research

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The Earth system is an integrated, self-regulating system under increasing pressure from anthropogenic transformation. The Earth System Science Partnership (ESSP), which was established by the international global environmental change research programs (i.e., DIVERSITAS, IGBP, IHDP and WCRP) facilitates the study of this system in order to understand how and why it is changing, and to explore the implications of these changes for global and regional sustainability. Crucial to this scientific enterprise are interdisciplinary Joint Projects on carbon, food, water and health. This paper analyses the scientific and institutional evolution of ESSP as a framework for interdisciplinary and integrative research of societal relevance. Case studies on food systems, carbon budgets, water security and biodiversity conservation illustrate how these projects have advanced integrated Earth system knowledge. At the institutional level, we explain the transformation of the ESSP governance and how this has further enabled interdisciplinary research. The lessons learnt from ESSP research can contribute to the development of the next generation of Earth system science for sustainability.

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Introduction

The Amsterdam Declaration, endorsed by participants at the 'Global Environmental Change Open Science Conference' in 2001 [1], describes the Earth system as a single, self-regulating system under rapid human transformation. It recognized both the scientific progress of the international Global Environmental Change (GEC) research programs (DIVERSITAS: the International Programme on Biodiversity Science; IGBP: International Geosphere-Biosphere Programme; IHDP: International Human Dimensions Programme for Global Environmental Change; and WCRP: World Climate Research Programme) and the need for a new partnership to further advance and integrate Earth system knowledge [2]. Acting on the Declaration, the four GEC research programs created the Earth System Science Partnership (ESSP). The ESSP facilitates the study of the Earth's environment as an integrated system in order to understand how and why it is changing, and to explore the implications of these changes for global and regional sustainability [3••]. A critical component of this scientific enterprise is the set of interdisciplinary Joint Projects on carbon, food, water and health.

The nonlinearity and complexity of natural and social processes are recognized and policy makers pose questions for which solutions require collaboration between various stakeholders (e.g., researchers, decision makers, engineers, private sector representatives). For instance, the problems of food, water and energy security need to be tackled in more holistic way, allowing for a variety of different systemic feedbacks and inclusion of the expertise of many different disciplines. Working in their respective fields, the resulting ESSP Joint Projects integrate Earth system knowledge and contribute to the quantification of risks posed by GEC. The future solutions, however, will also have to be built on the knowledge beyond the research community.

This paper critically assesses a decade of ESSP activities and draws conclusions of what can be learnt from all these effort to aggregate, integrate and synthesize GEC research. Such an assessment is especially important considering current plans for a new Earth System Sustainability Initiative, called Future Earth, which will shape the next generation of GEC research. This initiative is currently being planned by the International Council for Science (ICSU) and the International Social Science

Council (ISSC) in collaboration with the Belmont Forum (BF[9]) and other international organizations (e.g., UNEP and UNESCO) [4]. Future Earth strongly builds on experiences from current international GEC research but it calls for a stronger focus on joint research efforts by natural scientists, social scientists, humanists and engineers, and for working with stakeholders/users to contribute to the co-design of a globally and regionally sustainable future.

The genesis of ESSP

The chairs and directors of the GEC research programs met annually throughout the 1990s to exchange information about scientific progress of their individual core projects and networks, and to identify potential areas of future research. These meeting were rather informal. However, with increased recognition of Earth as an integrated system, the chairs and directors started to consider how to embark on more collaborative, interdisciplinary Earth system research. In the late 1990s, therefore, they envisaged an additional research structure geared toward issues of greater interest to society at large. Rather than disciplinary focused research, novel interdisciplinary GEC research was proposed to address also the societal dimensions of complex themes such as carbon, energy, water resources, food security and health. Realizing that input for such endeavors would need to come from a range of disciplines, the chairs and directors discussed the necessity of a partnership with joint inputs from all programs. The chairs and directors therefore agreed to initiate a set of Joint Projects with members of the GEC research community dealing most closely with these issues [5]. In 2001, the Earth System Science Partnership (ESSP) was launched by DIVERSITAS, IGBP, IHDP and WCRP. In addition the Global Change SysTem for Analysis, Research, and Training (START) also became a partner of the ESSP. START, established in 1992, is a capacity building and research network co-sponsored by IGBP, IHDP and WCRP. Despite having no institutional home (secretariat) or significant resources (except initial GEC program support) to operate this new scientific framework (see also 'Transformation' section), it was envisioned that the ESSP would become an innovative approach for harnessing more relevant for society research benefiting from the expertise of the GEC research community.

The enthusiasm and willingness of the GEC research programs to work together in the early stages of ESSP's existence greatly stimulated the development of the Joint Projects: The Global Environmental Change and Food Systems (GECAFS [Ingram JSI: **From food production to food security. Developing interdisciplinary, regional-level research**, PhD thesis, Wageningen University, Wageningen, 2011]) and the Global Carbon Project (GCP [6]) were both established in 2001. At the same time, planning started for the third Joint Project, the Global Water System Project (GWSP [7]), which established its international project office in 2004 and launched its Science Plan and Implementation Strategy one year later. Global Environmental Change and Human Health (GECHH [8]) was planned at a later stage with the science plan and implementation strategy launched at the ESSP Open Science Conference in 2006 and established an operational project office in 2010. Each of the Joint Projects created research networks and published their own Science Plan and Implementation Strategy. The unique scientific niche of these projects was also identified, drawing on expertise and synthesized knowledge of the core projects and the GEC research community. New types of science products emerged and formal partnerships established with a range of UN agencies and other national and international bodies.

Below we discuss programs, partnerships, Joint Projects, core projects and networks. These are defined in the lexicon of GEC research (Table 1).

Transformation

The governing body of the ESSP, for the first six years of its existence (2001–2006), consisted of the chairs and directors of the GEC programs. This body made the executive decisions and the Joint Project Executive Officers were invited to provide scientific input to the meetings. In September 2005, with financial support from the National Science Foundation (USA) and other funders, a small ESSP Coordination Office was established. International Project Offices were also established and the Joint Projects began to develop impressive networks of researchers involved in Joint Project interdisciplinary research. By 2006 around ten professional staff were involved in research coordinating activities and hundreds were actively pursuing the research agendas of the Joint Projects.

Governance challenges

An integrated approach to the study of the Earth system is not only scientifically complex but it is also challenging at the institutional level. For example, despite their commitment to ESSP, the programs had to manage (and prioritize) challenges and opportunities of their own individual activities and constituents. The need for an improved governance structure that would ensure representation of all components of the ESSP, soon became evident. Therefore, at the 2006 meeting in Tutzing, Germany, of the chairs, directors and the Joint Projects and ESSP officers proposed to establish a Scientific Committee (SC) for the ESSP. The SC included: firstly, proportional representation by each of the sponsoring programs; secondly, representation for the ESSP Joint Projects, START and other major ESSP activities

[9] The Belmont Forum is an international Alliance of funding agencies who support GEC research.

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Table 1

The lexicon of global environmental change organizations.

	Definitions	Organizations
Global environmental change programs	Programs are legally recognized scientific organizations that coordinate GEC research. They are co-sponsored by major agencies, such as the International Council for Science, the United Nations Educational, Scientific and Cultural Organization and the World Meteorological Organization.	DIVERSITAS, IHDP, IGBP, WCRP
Partnerships	Partnerships are in-formal arrangements established by the GEC research programs to exchange ideas, synthesize and communicate integrative GEC research findings and conduct interdisciplinary research.	ESSP
ESSP joint projects	Joint Projects are sponsored by at least three GEC research programs, promoting interdisciplinary research across disciplinary boundaries (natural and social science). The ESSP Joint Projects are designed to directly address the two-way interaction between GEC and global and regional sustainability issues. The Joint Projects also benefit from the expertise and synthesized knowledge of the Core Projects and the GEC research community.	GCP, GECAFS, GWSP & GECHH
Core projects	Core projects are disciplinary enterprises sponsored by one GEC research program, designed to research one specific field/scientific challenge.	For example, bioGENESIS (DIVERSITAS); Integrated Land Ecosystem-Atmosphere Processes Study (IGBP); Urbanization and Global Environmental Change (IHDP); Stratospheric Processes And their Role in Climate (WCRP).
Regional networks	Regional networks provide opportunities to enhance GEC research and networking capacity, particularly in developing countries.	Asia-Pacific Network for Global Change Research (APN), Inter-American Institute for Global Change Research (IAI), and global change SyTem for Analysis, Research, and Training (START).

(e.g., Integrated Regional Studies); and finally, representation from 'outside' the ESSP network. The SC should be led by an independent chair, appointed by ICSU. In this way the ESSP governance structure resembles more closely that of the sponsor programs.

Partnership or program?

At the same meeting, the possibility of all four programs and the ESSP moving toward a unified, well-structured integrated GEC research program was considered. The motivation for transforming the ESSP from a loose scientific partnership into a legally recognized integrated program was simple: to increase visibility for this scientific enterprise, attract more resources and contribute to the advancement of interdisciplinary Earth system science. As part of this long-term vision, it was agreed that the ESSP would become a program. This decision was also supported by ICSU. However, some of the partners stated that considering the sheer magnitude of this change, there should be a community-wide consultation process and this decision was not implemented. Several advantages and disadvantages of ESSP becoming a program were noted by various partners. The advantages, for example, included:

- an ESS program would complement the four GEC programs by having its own intellectual agenda and mechanism (activities) to address cross-cutting topics that the Joint Projects, START, integrated regional studies and the GEC programs cannot cover alone. It would therefore not overlay the four GEC programs as a superprogram, it would become a fifth endeavor of a highly integrative nature, closely linked to policy and other stakeholder interests;
- the ESSP would evolve as a coherent program through which all common scientific and advisory endeavors would operate in a consistent and strategic mode; and
- the new program structure would not lead to any diminishing engagement from any of the GEC programs — quite the contrary, it should help either to avoid or more easily deal with the kinds of conflicts of interest among the GEC programs that made the partnership difficult to manage at times.

The disadvantages, for example, included:

- although there was strong support for strengthening, and improving the governance and management of ESSP, and, most importantly, for advancing and further integrating Earth system science, this could also be achieved if the ESSP remained just a partnership; and
- the ESSP was not ready yet to become a program because operational funds were limited. IGBP and WCRP already had a strong interest and investment in

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Earth system science and a new program focusing on the Earth system could become a competing program regarding agenda setting, involvement of scientists and funding.

The ESSP Scientific Committee: a new voice for interdisciplinary research

The chair and director's meeting at the ESSP Open Science Conference in Beijing confirmed that ESSP would remain a partnership but now with the establishment of a SC. The next step was to establish the ESSP SC. The SC finally involved two ICSU-appointed members and the chair, GEC research programs chairs and directors, an ICSU representative, representatives of each Joint Project, integrated regional studies and START. There was a community-wide search for a Chair, who should be a well-respected scientist with interdisciplinary experience, who could advance ESSP by connecting existing activities of the GEC programs and ESSP, and who would enable new collaborative research opportunities with international organizations. Professor Rik Leemans (Wageningen University, The Netherlands) was nominated by the GEC programs and appointed by ICSU as the first Chair of the ESSP Scientific Committee. The inaugural ESSP SC meeting convened in 2007 in Paris. The chair participated in all governing meetings of the GEC programs, stimulated the development of several common activities between joint and core projects (e.g., the Climate-Convention Dialogue), and established a GEC synthesis/review journal [9].

Review of ESSP

In 2008, an ICSU–IGFA review of the Earth System Science Partnership was completed [10]. The motivation for this review was to assist the further development of the ESSP. More specifically, despite scientific advances by the Joint Projects, there was concern that ESSP had not advanced as much as anticipated. The analysis of the review panel was based on a dialogue with the chairs and directors, ESSP and input from ICSU, IGFA and the wider community through questionnaires and interviews. The review provided guidance on options for the future. The panel elucidated that the ESSP was now more relevant than when it was established in 2001: There was a need for a robust ESSP. Key improvement areas were identified: firstly, ESSP must develop a stronger scientific focus; secondly, ESSP's structure should be driven by its scientific mandate with input from users; thirdly, ESSP must critically engage with the wider community; and finally, ESSP should continue its strategic and comprehensive approach to capacity building. Additionally the panel noted that current funding was insufficient to fulfill ESSP's mandate. The Panel was convinced that 'the status quo will inevitably result in a progressive decline of the partnership,' and thus, it recommended that 'the ESSP formulate as soon as possible a long-term vision of where it wants to be in 10 years time' (p. 8 in [10]).

In response to the review, the ESSP developed a common strategy for integrative global environmental change research and outreach [3••]. This strategy describes an internationally coordinated and holistic approach to Earth system science. The basic premise of this 'holistic' approach is to further enable interdisciplinary research — at the global and regional level — to integrate and synthesize knowledge from the natural and social sciences. This is important because no single discipline, program or nation alone can respond effectively to the increasing pressures by human transformations of the Earth system. The ESSP started to implement its integrative research and outreach strategy by developing new services that included knowledge products, Earth-system science dialogues, a synthesis journal for interdisciplinary collaborative research, and tighten its cooperation with policy makers. These activities have helped elevate ESSP's profile.

ESSP concept revisited

Institutionally, the ESSP still remains a loose partnership of four GEC programs with no legal status. The programs and their core projects have contributed considerably to the ESSP scientific enterprise. However, programs and ESSP competed for resources at times but this did not limit interdisciplinary interactions and the creation of a more holistic strategy for integrated global environmental change research and outreach. Most of the ESSP's scientific activities rely on voluntary contributions of many researchers, who have demanding jobs at research institutes and universities throughout the world. There are ample opportunities for scientists to become involved in interdisciplinary research [11]. Education, career and funding opportunities could, however, better reflect the importance of such an integrated research approach, which contributes to the understanding of major societal challenges.

Facilitation of global environmental change research

The research core of the ESSP is its set of Joint Projects. Their results are based on independent, participatory (both bottom up and top down approaches) and state-of-the-art science and coordinated international research initiatives. One of the main strengths of the Joint Projects is that they help assemble social and natural scientists to integrate different disciplinary concepts, tools, data and methods. Over the past decade, these Joint Projects have developed their own methodologies and approaches to build the scientific infrastructure that allows for a more integrated approach [3••]. Schmidt and Moyer [12], for example, describe the ESSP Joint Projects as an outlet for a new generation of interdisciplinary researchers.

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ESSP and the four GEC programs organized the first ESSP Open Science Conference in Beijing, China, in November 2006 with the focus on 'Global Environmental Change: Regional Challenges.' Conference highlights included the launch of the first ESSP integrated regional study (Monsoon Asia Integrated Regional Study, MAIRS [13], which was coordinated by START with support from particularly the Asia-Pacific Network for Global Change Research (APN)), the publication of the science plan of GECHH and the presentation of the first annual global carbon budget and trends by GCP. However, while the conference sessions presented advances in GEC research from many disciplinary perspectives, collaborative research results between social and natural scientists remained limited.

To synthesize emerging GEC and sustainability research, the ESSP SC established a new journal 'Current Opinion in Environmental Sustainability' (COSUST), where advances in earth system and sustainability science, and science plans can be published in timely review and synthesis papers [9]. The interdisciplinary journal addresses all the environmental, economic, social, technological and institutional aspects of the sustainability challenges by integrating scientific insights and societal practices and processes. The almost immediate inclusion of COSUST in the Web-of-Science ISI journal database attested the success of this endeavor.

A crucial element of ESSP activities is its continuing dialogue with policy makers. Two pathways emerged by which the ESSP community contributes to decision-making processes and actively engages itself with both informing and shaping international policy agendas. First, numerous researchers who are closely involved in ESSP activities are also involved in various global science-policy assessments [14]. Examples include the Millennium Ecosystem Assessment, the IPCC Assessment Reports, UNEP's Global Environmental Outlook series, the triennial World Water Development Reports and various reports for international organizations, which draw knowledge from ESSP networks [15]. In recognition of its credible scientific achievements, ESSP recently signed an agreement to coordinate UNEP's scientific review of the next Global Environmental Outlook series. GEC research results are also communicated to policy communities (e.g., through the UNFCCC-Subsidiary Body for Scientific and Technological Advice dialogue) and other stakeholders. These dialogues also help to further focus research agendas on policy-relevant and timely societal issues and lay foundations for the future co-design of policy relevant projects that need an integrated approach to tackle the complex nature of global environmental change.

The ESSP, particularly through its Joint Projects, has promoted collaborative efforts with international organizations. For example, joint collaboration with the Scientific Committee on Problems of the Environment (SCOPE), UNESCO and UNEP resulted in policy briefs with GCP on the carbon cycle and GECAFS on food systems and environmental change. A major legacy of GECAFS (which ended by synthesizing its findings in 2011 [16]) was the link with the Consultative Group of International Agricultural Research (CGIAR) that led to the development of long-term ESSP-CGIAR collaborative research on Climate Change, Agriculture and Food Security (CCAFS [17]). CCAFS unites the complementary strengths of the CGIAR system and the ESSP to mitigate and adapt to climate change, which is one of the most pressing and complex challenges to food security in the 21st century.

Scientific achievements and lessons learnt

The Joint Projects are operated by officers with professional research and coordination experience, supported by a major host institution and often with several regional offices. They integrate the disciplinary perspectives and scientific advances of the GEC programs and enable new interdisciplinary research, under the leadership of the ESSP's SC and the Joint Projects' Scientific Steering Committees. Many lessons can be learnt from ESSP's experiences. The accomplishments of the Joint Projects to a large extent reflect the number of years they have operated to date.

GECAFS was established as a 10-year joint project and concluded in March 2011. In addition to substantial scientific and other outputs (see below) GECAFS identified many lessons on how to establish and deliver an interdisciplinary agenda on food security [22], aimed at assisting policy formulation and resource management, and at regional level — the three main 'charges' from the C&Ds. The first step was to establish formal, strategic partnerships with key international bodies: FAO, CGAIR and WMO. This helped increase visibility on international stage, bridge science and development agendas, the way for uptake of result and provided fundamental inputs to early planning and throughout the project.

GECAFS's objective was 'to determine strategies to cope with the impacts of GEC on food systems and to assess the environmental and socioeconomic consequences of adaptive responses aimed at improving food security.' This was derived at following many discussions with a range of stakeholders, and culminated in clear wording targeting policy and management, that stresses adaptation, and that emphasizes both socioeconomic and environmental consequences (i.e., trade-offs and synergies). GECAFS outputs included both formal science products and also improved approaches to deliver societal-relevant research. Drawing on the extensive (yet distinct) literatures built up by the food-chain and food-security communities, a key science innovation was the GECAFS food system concept [18,22] (Figure 1). By linking these two literatures, the concept systematically

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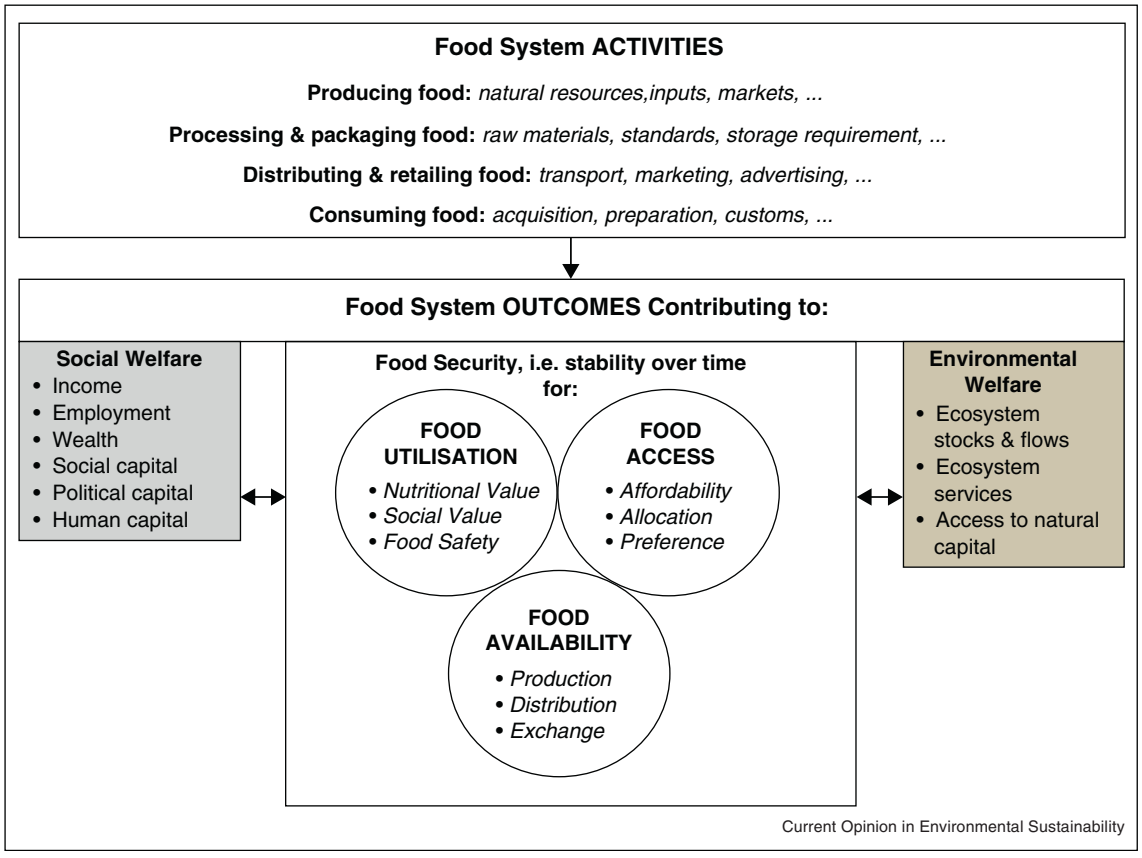
Figure 1



Food system activities and outcomes.
Adapted from [18] and Ingram JSI: **From food production to food security. Developing interdisciplinary, regional-level research**, PhD thesis, Wageningen University, Wageningen, 2011.

integrated the 'what we do' (the *Activities*) with the 'what we get' (the *Outcomes*), and allows for a systematic analysis of the consequences of adaptation ('doing the Activities differently') for the suite of all nine elements (bullet points in Figure 1) that collectively define food security. The concept has now been adopted by major agencies including the FAO and CGIAR (via CCAFS).

Further outputs included improved scenarios methods [19,20] and approaches for improved stakeholder engagement, and particularly at the regional level [21]. A major synthesis of GECAFS outputs has also been published [16]. This helped to identify and integrate the links between several food system activities 'from plough to plate,' and the consequences of these activities for the well-established food security components of food (availability, access to food and food utilization). There were several main messages. *Systems approaches can help improve our understanding* of the interactions between global environmental change and food security, and thus of the range of policy options available to address them. Systems approaches connect the activities of food producers, processors, distributors, retailers and consumers to food security and environmental outcomes. This frames these activities as dynamic and interacting processes embedded in social, political, economic, historical and environmental contexts. Food systems operate across multiple scales and on a range of levels within all their different dimensions. Food systems can be conceptualized as coupled social-ecological systems, in which vulnerability arises from multiple stressors operating across different dimensions (e.g., temporal, spatial, and institutional) and scale levels on them (e.g., micro to macro). As the nonspatial dimensions are very relevant to food security/GEC interactions, research has to recognize, and engage with, a wide range of stakeholders. Stakeholder dialogue plays a particularly important role in agenda setting and a range of methods including consultancies, workshops and informal approaches may need to be employed. Most researchers and organizations in the 'food security' domain only consider agricultural issues; a new cadre of researchers and policy makers is needed on the broader food security agenda. Setting such an agenda that is relevant to regional (as opposed to global and/or generic) issues needs a highly

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consultative and inclusive approach. The utility of the GECAFS food system concept in framing and delivering research work was further refined by Ingram [22].

Another key aspect that GECAFS highlighted is that interdisciplinary research is best established from 'neutral' territory, that is its development should not be led by any given discipline but collaboratively from the outset. This is because — however open a discussion is intended — if the initial thinking is from a given discipline, the agenda is already 'flavored.' Initially GECAFS started from a crop-science viewpoint and considered what needed to be added to approach food security. It thereby reached out to social and human security scientists. But it was quickly realized that a fresh approach was needed: '*you can't just 'bolt on' social science!*' The best approach was to draft a question which would attract the necessary disciplines but without disciplinary 'spin.' This necessarily needed very simple language: '*How will GEC affect our ability to feed ourselves?*,' rather than a more-disciplinary question such as '*How will GEC affect food production?*' Many early drafts were therefore discarded in favor of a 'clean page' headed by this 'simple' question, and this page was then populated with increasing detail leading to researchable questions which maintained disciplinary balance at every step. Each research question required an active interaction between disciplines. Determining the 'final' interdisciplinary research agenda took some years. This was essentially due to the highly iterative way in which conceptual and regional research was planned and developed iteratively over time. While time consuming, it both established conceptual and methodological research on generic topics (e.g., food systems, vulnerability, scenario and decision support) based on science and policy issues identified in regional projects, and policy-relevant research at the regional-level on impacts, adaptation and feedbacks (based on improved conceptual understanding and methods). This both advanced science and addressed regional information needs, and helped link the international GEC science agenda with regional issues.

A related lesson was that *disciplines have differing viewpoints* on 'food security.' For instance, social scientists may think in terms of entitlement to food, economists in terms of food affordability, the humanities in terms of the social function of food, and biophysical scientists in terms of crop growth. None alone address food security but all are equally valid aspects and all have an important contribution to make. Varied views need to be considered for all highly integrated, societal-level questions of this type; research on food security (as with research on other societal-level 'securities' such as water security and energy security) requires balanced interdisciplinarity. The early years of GECAFS involved constant learning on *how* to address the charge, and the formal GECAFS science plan was not published until year five of the project.

GEC research at the *regional-level had not been as prominent as at global and local levels*, yet is an important spatial level for food security, food system research and GEC considerations [22]. Similarly, food 'security' research (in fact, usually food 'production' research) has been more prominent at local and global levels. But a range of jurisdictional issues also arise when working at regional level. Food security research planning and delivery therefore has to encompass the notion of a range of spatial, temporal, jurisdictional scales, and multiple levels on each.

Further, effective implementation of food security research at regional level necessarily involves *complex interactions between multiple stakeholders*, all of whom have their own objectives and motives. It is therefore important to identify who the stakeholders are in the GEC-food security debate at the regional level, when to engage them in research planning, and how. Participatory research methods such as consultations, surveys and scenario exercises are effective ways to achieve this. It is important also to engage stakeholders in the co-production of knowledge, as far as possible. This means engagement in the research process itself, although it must be remembered that stakeholders are heterogeneous groups representing multiple interests in GEC science; and they choose to participate in various stages of the scientific process, seldom participating in all [23].

In addition to innovative science planning and delivery approaches, addressing this charge required innovative project governance and funding approaches. *The governance* of research to address the charge needed to learn from the programs' Core Project experience, but be modified to allow the stronger input from nonresearch stakeholders. GECAFS governance was therefore designed to foster the necessary interactions between a wider stakeholders community: international agencies, donors as well as researchers. A Scientific Advisory Committee was established comprising representatives from such groups; and an Executive Committee charged with implementation comprised representatives from the sponsoring program secretariats. This avoided an approach based on a single Scientific Steering Committee, which had to deal with both strategy and detail. It also helped ensure uptake of research results by leading collaborating agencies (e.g., FAO and CGIAR). GECAFS *funding strategy* was dependent on developing a research agenda that would appeal to both science and development donor communities. The continual core funding (from the Natural Environment Research Council of UK) was instrumental in levering research funds from some 25 different science and development agencies.

The GCP focused largely on the development of value-added integrated products which built upon more disciplinary research. These products include from the

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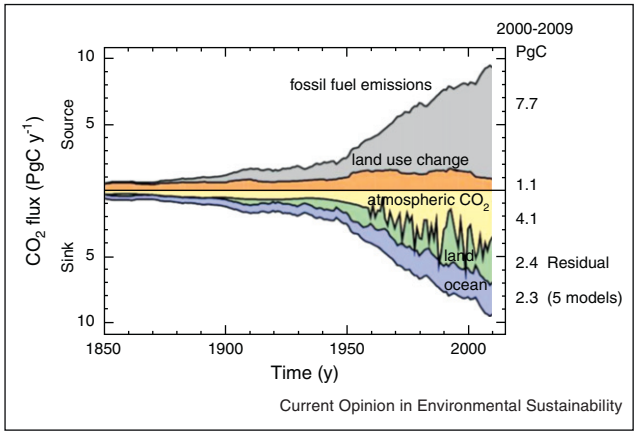
establishment of annual updates of the global CO_2 and CH_4 budgets to the assessment of the size of carbon pools and their vulnerabilities to changes in climate, land use, and resource extraction [24,25]. Although with a strong focus on global science, the GCP develop strategies to bridge seamlessly global and regional agendas through the engagement of scientists from all over the world to work on one common objective: the establishment of CO_2, CH_4 and N_2O regional budgets and their attribution to the main underlying processes (see Figure 2 and [26]). The power of this approach is that regional budgets can be further constrained with the knowledge of the neighboring regions and global budgets, while global budgets can be disaggregated and attributed to regions which will help to identify the processes driving carbon sources and sinks. Thus, all contributors have something to gain regardless of their primary interest. Vastly different approaches that include top-down and bottom-up methods to estimate fluxes bring some of the most interesting interdisciplinary sciences together. The global analyses have critical links to international climate change negotiations and scenario development, while the regional budgets bring more connections with national interest in climate policies and mitigation strategies, and therefore to broader user and policy communities. This development began with the establishment and communication of the annual state of Global Carbon Budget [27–29] and expanded with the regional focus by the REgional Carbon Cycle Assessment and Processes (RECCAP; [30,31]) aiming to establish the mean and variability of regional carbon budgets at subcontinental and ocean basin level. This is an ongoing assessment with major milestones and specific set of research products in the form of 14 regional carbon balances and 10 global analyses and datasets supporting the regional analyses. The focus on key research products keep the assessment in check and the engagement of the research communities, while an expanded assessment can work on longer time scales to support and develop capacity building in regions with least capacity to undertake complex model simulations and data analyses [32].

Other key lessons learned through a diverse portfolio of GCP activities is the importance and need of playing the dual role of a broker for community consensus and an explorer of novel science likely to become important but not yet embraced by the broader community. Examples in the first category include global synthesis on the size and distribution of the permafrost carbon pools [33] and the role of global forests as carbon sources and sinks [34,35]. Examples of the second category are exploring the links between the kaya identity and anthropogenic emissions and carbon sinks [36,37], the role of climate and resource extraction from methane hydrates [38], human interactions and emissions from drained tropical peatlands [39], and the role of the southern ocean as a carbon sink [40]. Timely contributions to influence specific policy outcomes are important and require a 'SWAT' approach to bring together a team of experts willing to contributing in shorter time scales than the ones usually driving more standard research contributions. Examples are the role of the tropical forests in climate policies [41] and the ability of science to separate out the direct from the indirect human influences on carbon sources and sinks [42]. Breaking new ground to bring concepts of carbon management to the city level has led to the development of a new network of scientists to advance urban carbon, energy, and water analyses and modeling [43].

The third ESSP Joint Project is the GWSP. One of the main products of this project is the Digital Water Atlas, a public depository of maps and datasets indicating the state of freshwater at a global scale. GWSP develops strategic partnership within the ESSP network. One of the recent collaboration projects with researchers from freshwater project of DIVERSITAS yield in a well-recognized publication where the potential for conflicts between 'human water security' versus that of biodiversity were exposed [44]. The global analysis, including 23 threat factors which may stress water for humans and nature, shows that most of the places where human water security is currently maintained are also those where freshwater biodiversity faces the greatest threat (Figure 3).

GECHH, as the newest Joint Project with a science plan [8] that was agreed upon in 2006 by DIVERSITAS, IGBP and WCRP and only later by IHDP faced several additional challenges in its early stages. First and foremost, GECCH had to integrate researchers from the health community with researchers from the more traditional GEC communities in the natural and social

Figure 2



The evolution of the anthropogenic perturbation of the global CO_2 budget since 1850. Right column shows the average flux values for the decade 2000–2009 [28].

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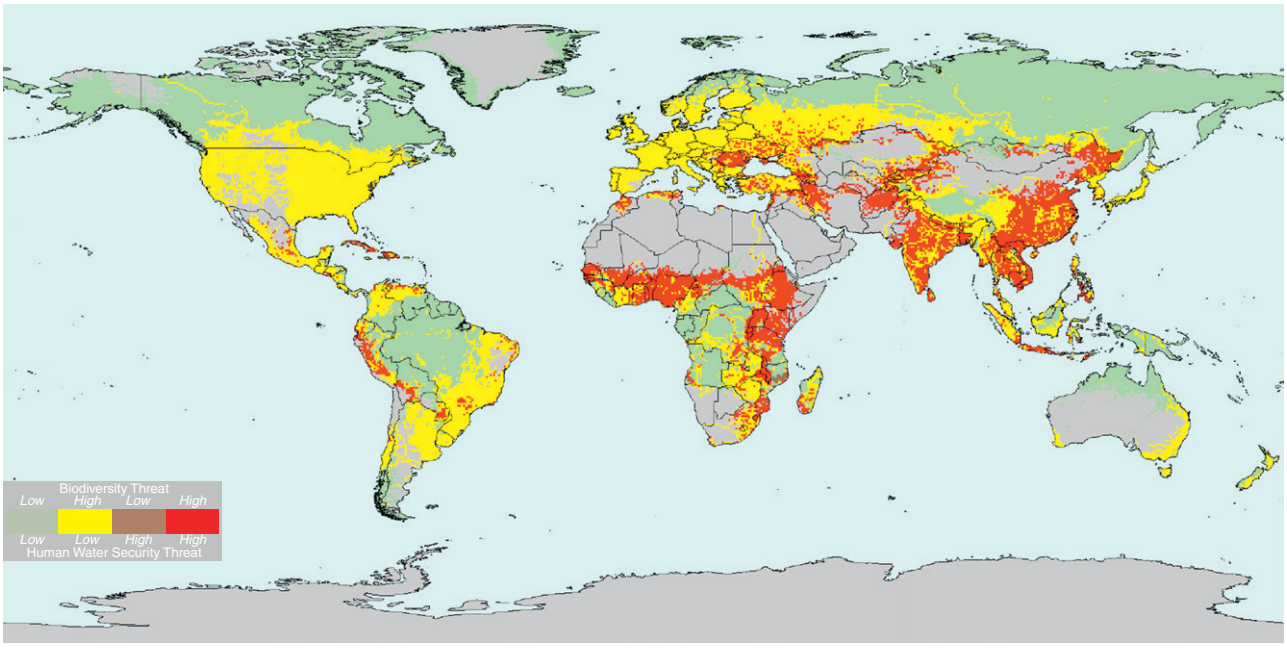
Figure 3



Prevailing patterns of threat to human water security and biodiversity [44].

sciences. Secondly, starting a new Joint Project at a time when ICSU, the ISSC and other sponsors were starting to consider the future of the GEC programs and ESSP made it difficult to secure its own funding. A third challenge for GECCH has been to develop simultaneously an international profile within three science communities (natural sciences, social sciences, and health sciences) and products of wider public interest in a manner similar to the Carbon and Water Projects. Partly, this is a function of the time that GECCH has been effectively running (less than two years).

In contrast to the GECAFS approach, the GEC programs and ESSP decided to write a science plan before the opening of the project office. This had two unforeseen consequences. First, no one anticipated the complexities of drafting a science plan which needed to take into account not only the traditional science communities of the GEC programs, but also required greater input from the social science and health science communities. Finding a consensus among the various groups represented in the writing team and then gaining acceptance by the four GEC programs took longer than anyone anticipated. For example, at the launch of the GECHH science plan at the ESSP Open Science Conference in Beijing in 2006, IHDP had still not agreed to the science plan because of concerns about the lack of social science input. As a result, the final agreed science plan was not accepted by IHDP until 2008. Clearly, the contrasting experience of GECHH and the other Joint Projects suggests that more thought needs to be put into both what is required in a science plan and the processes required to launch Joint Projects. Despite these different implementation approaches, the Joint Projects have advanced to achieve considerable scientific success, as described in this paper. The programs and their core projects have also contributed considerably to the ESSP scientific enterprise.

Opportunities and challenges

Increased recognition of an integrated Earth system under rapid anthropogenic change prompted the GEC programs to articulate the need for integrated research of the Earth's environment in order to understand why and how it is changing, and to explore the implications of these changes for global and regional sustainability. This also led to the Visioning Process sponsored by ICSU and ISSC aimed at setting new priorities for an international research for global sustainability [45]. On the basis of a series of consultations (with ESSP, the GEC programs and others), the five Grand Challenges (Box 1) in Global Sustainability Research were developed to provide a framework of future research direction [4,45]. This process is likely to initiate a change of the institutional structure of GEC research. It is, however, essential that the ESSP Joint Projects, START, MAIRS and other existing GEC research activities should become integral

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Box 1 The five 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 behavioral changes can enable effective steps toward global sustainability.
5. Innovating — Encourage innovation (coupled with sound mechanisms for evaluation) in developing technological, policy and social responses to achieve global sustainability.

to any new effort to tackle the five grand challenges of Earth System and Sustainability Research.

Considerable scientific achievements have been accomplished within the ESSP, such as the design and implementation of an innovative food systems conceptual framework; an annual carbon budget trends and analysis; and a global analysis on human water security and biodiversity conservation. Understanding regional environmental change and its implications for local sustainability have been a critical area for the ESSP, as illustrated by the establishment of an integrated study on Monsoon Asia in MAIRS, the GCP's RECCAP and GECAFS regional science plans in the Caribbean, Indo-Gangetic Plain and Southern Africa.

There are many opportunities and challenges related to interdisciplinary GEC research to which the Future Earth initiative can contribute. Any future enterprise needs to stimulate broad inclusion of researchers across the globe and across different disciplines (see Ref. [4]). As depicted by the Joint Projects, the ESSP has involved researchers from the social and natural sciences but many continue to believe researchers from the humanities and social sciences are under-represented in ESS research. The humanities are the least represented and yet their involvement is important [46]. For example, organizational and behavioral scientists can advance our understanding of the history, philosophy, social, behavioral, and management changes required to move society toward more sustainable pathways [47]. A global survey to assess engagement of social sciences scholars [48] identified the following priority research areas: firstly, equity/equality and wealth/resource distribution; secondly, policy, political systems/governance, and political economy; thirdly, economic systems, economic costs and incentives; and finally, globalization, social and cultural transitions. There are also many other scientists working on global environmental change issues who are not active within the network.

The new initiative should continue to contribute to the central tenet of interdisciplinary research: integration of knowledge. There still is a need for an improved understanding of the practice of 'integration' and how to better position knowledge from the scientific community (and other stakeholders) to help decision makers and society cope with emerging challenges in order to optimize opportunities for a more sustainable future. ESSP will continue to stimulate truly integrative research within the new design of the Earth System Sustainability Initiative (Future Earth). To achieve this, the inclusion of the user community and funders to co-design research questions and stimulate wider discussions on possible solutions is important. This requires a willingness to participate and become involved in a collective learning process to establish a common language and better integrate different epistemologies and timeframes. The pursuit of integrated research in the field of GEC will require a shift in our language and a fundamental reframing of the field itself. New integrated research should be supported by well-designed funding schemes that allow collaboration across disciplines and sectors, stimulating an integrated approach. The Belmont Forum promises increased integration and an opportunity to restructure funding practices [49].

One of the challenges in designing a new integrative research structure is to give it enough flexibility to allow the researchers to easily (re-)organize themselves to tackle emerging scientific questions and at the same time to provide a stable institutional home where they would find support of their scientific activities. Those structures should enable rapid and accurate responses to emerging opportunities and challenges on one hand, and on the other should create possibilities to foster strategic alliances to tackle complex societal challenges. For example, to ensure international participation in research projects, close collaboration with regional research centers on environmental change should be enhanced. Regional nodes have in-depth information about specific challenges unique to their respective region. Regional research networks, such as the APN, START, and the intergovernmental Inter-American Institute for global change research (IAI) contribute to environmental knowledge at the regional and global levels.

Paraphrasing Bogardi [50], without understanding social and political dynamics, aspirations, beliefs and values, and their impact on our own behavior, we only describe the world's physical, biological and chemical phenomena, observe and document their changes at different scales, and apply technology to secure access to resources but would ultimately fail to ensure sustainability. Interdisciplinary research that bridges disciplines and involves stakeholders can contribute to solutions for a sustainable world. There is no other viable way forward. The sustainability challenges must be met and the Earth system science community will have an important role.

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