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International Geosphere–Biosphere Programme and Earth system science: Three decades of co-evolution

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ABSTRACT

The maturing of Earth system science as a discipline has underpinned the development of concepts such as the Anthropocene and planetary boundaries. The International Geosphere–Biosphere Programme's (IGBP) scientific and institutional history is deeply intertwined with the development of the concept of the Earth as a system as well as the discipline of Earth system science. Here we frame the broader programme of IGBP through its core projects and programme-level activities and illustrate this co-evolution. We identify and discuss three phases in the programme's history. In its first phase beginning in 1986, IGBP focused on building international networks and global databases that were key to understanding Earth system component processes. In the early 2000s IGBP's first major synthesis and associated activities promoted a more integrated view of the Earth system informed by greater emphasis on interdisciplinarity. Human actions were seen as an integral part of the Earth system and the concept of the Anthropocene came to the fore. In recent years IGBP has increased focus on sustainability and multifaceted engagement with policy processes. IGBP closed at the end of 2015 after three decades of coordinating international research on global change. The programme's longevity points to its capacity to adapt its scientific and institutional structures to changing scientific and societal realities. Its history may offer lessons for the emerging Future Earth initiative as it seeks to rally international collaborative research around sustainability and solutions.

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1. Introduction

The concept of the Earth as a system, the academic discipline of Earth system science and the institutions created to understand processes that determine the past, present and future of the Earth are now well established. Founded in 1986, the International Geosphere–Biosphere Programme (IGBP) has had a pivotal role in the evolution of these ideas and institutions. Indeed, it has helped drive new levels of international coordination and interdisciplinary cooperation in pursuit of fundamental knowledge "that will serve as the basis for assessing likely future changes on the Earth in the next 100 years" (IGBP, 1986). This task required the development and use of some of the most significant conceptual frameworks of the Earth as a system and the impact of change on it. IGBP evolved in a context of international scientific collaboration that began in the early 20th century: this context was shaped by growing concerns about the environment as well as by the forces of globalization (Uhrqvist, 2014a,b).

In anticipation of the ending of IGBP in 2015, following three decades of intense activity, in 2012 the programme launched an overarching synthesis with three principal strands: Earth system science, the Anthropocene, and core-project history and accomplishments. The present paper is a contribution to both the first and third strands. The overall objectives of this paper are to provide: (1) a broader programme-level framing for the individual IGBP core-project synthesis papers in this volume (Suni et al., 2015;

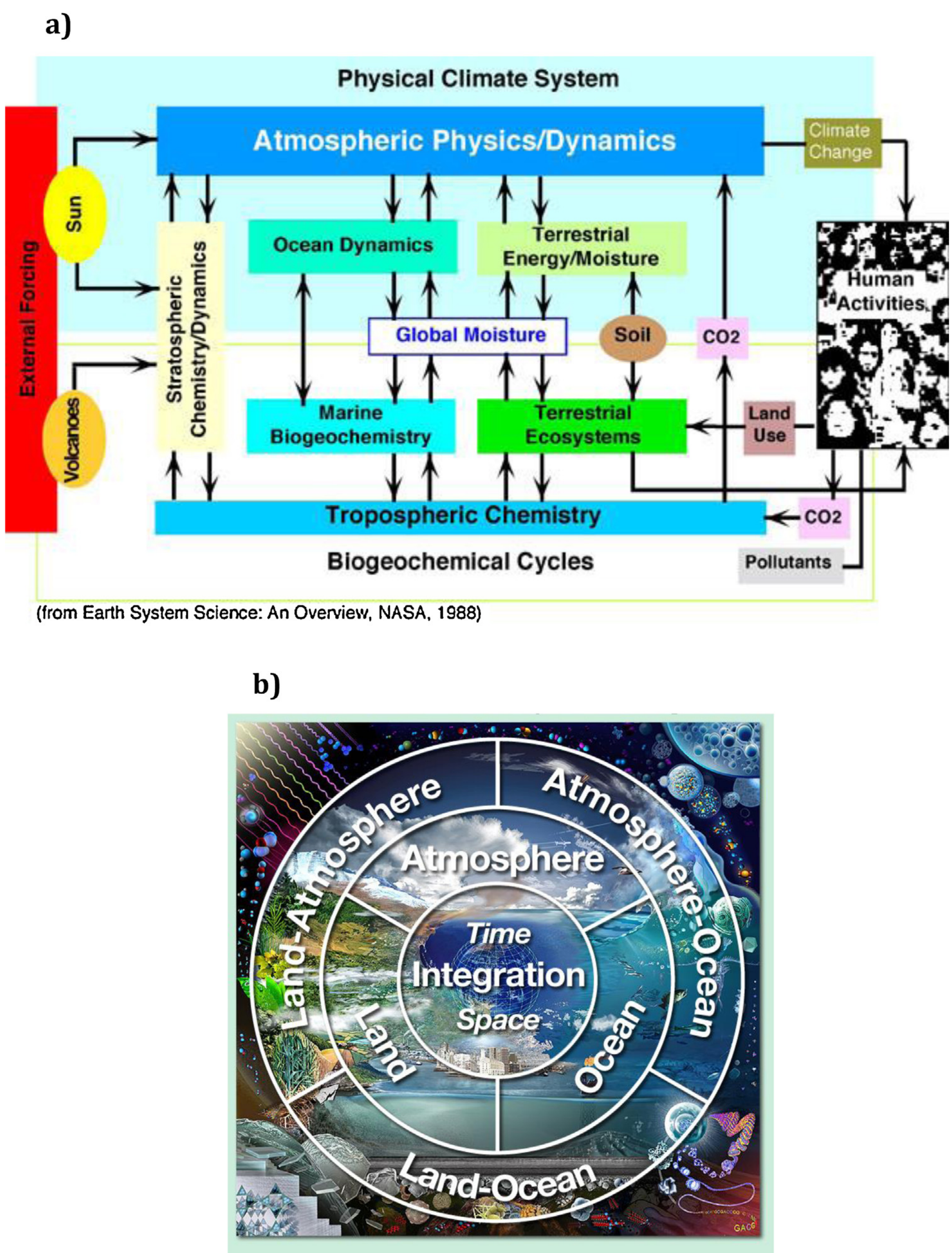

Fig. 1. (a) A conceptual model of the Earth system from NASA's Earth System Sciences Committee (NASA Advisory Council, 1986) often referred to as the Bretherton diagram. (b) IGBP phase 2 structure in which core projects conformed to either individual components of the Earth system, the interfaces between them, or integration across the Earth system components (Box 1 and Fig. 2).

Brévière et al., 2015; Hofmann et al., 2015; Melamed et al., 2015; Verburg et al., 2015; Schimel et al., 2015; Ramesh et al., 2015), and (2) an overview of how IGBP's scientific and institutional structure contributed to developments in the field of Earth-system science and international environmental policies.

This co-evolution process involved three major phases: Phase One, from 1986 to around 2000; Phase Two, from 2000 to around 2010; and Phase Three, between 2010 and 2015 (IGBP, 2006). The first phase focused on building international networks and understanding Earth system component processes. The second phase began with IGBP's first major programme-wide synthesis and promoting the interactions between components of the Earth system, which required greater emphasis on interdisciplinarity. Human actions were seen as an integral part of the Earth System and the concept of the Anthropocene came to the fore. The third phase was characterized by an increased focus on sustainability and greater engagement with the policy process. Integration with social sciences, co-design, and communication heralded a new era in international coordination with the emerging Future Earth initiative (Future Earth, 2013). Materials used to develop this paper were drawn from the IGBP archive (published documents and grey literature now available through the International Council for Science), personal communications, reviewed academic publications on IGBP and from published academic papers by those within the IGBP network and beyond. The ending of IGBP in 2015 to make way for Future Earth presented a unique opportunity for those closely affiliated with IGBP to reflect on this material to develop an overview of IGBP evolution and impact.

This approach is distinct but complements historical analyses of Earth system science progression in IGBP that have focused on aspects of the development of natural and social interactions (Kwa 2005; Mooney et al., 2013) or the constitution of the Earth system as a knowable and governable object in environmental science and policy (Uhrqvist, 2014a,b).

2. The early days

The origins of IGBP can be traced back to the first International Geophysical Year (1957) (IGY) as well as the launch of the International Biological Programme (1964) (Daniel, 1990; Uhrqvist, 2014a,b). IGY set a new level of ambition for international cooperation among geophysical scientists. In 1967, the Global Atmospheric Research Programme was launched (Perry 1975). A growing concern among scientists, politicians and civil society about the global environment culminated in the United Nations Conference on the Human Environment in 1972 (Stockholm). One of the outcomes of that conference was the establishment of the UN Environmental Programme (UNEP) to coordinate and promote environmental activities in the UN system.

Climate change began climbing up the political agenda in the 1970s. Its potential impact on societies prompted the first World Climate Conference in 1979 to assess the state of knowledge of the climate. A tangible outcome from the conference appeared a year later in the form of the newly established World Climate Programme (WCP) and its research arm, the World Climate Research Programme (WCRP).

The original sponsor of IGY, the International Council for Science (ICSU), emerged on the scene again in 1985 when it appointed an ad hoc planning group first chaired by Sir John Kendrew, President of ICSU, and later by Professor Bert Bolin, a Swedish Meteorologist, to scope out an international research programme on the "global dimension of chemical and biological processes" (IGBP, 1986, 1987). This came from a view that geophysical disciplines such as atmospheric physics and chemistry, ecology, geography, oceanography and marine biology, which had traditionally worked more independently, needed to conceptualize the Earth as an interactive system and frame their work in that context. The establishment of this planning group was to an extent motivated by Thomas F. Malone who had been persuading ICSU for a number of years to seriously consider in its future programmes the interactions between the physical and biological worlds and humanity (Malone, 2014).

In May 1986, NASA published "Earth System Science Overview—A Programme for Global Change" written by NASA's Earth System Sciences Committee chaired by meteorologist Francis Bretherton (NASA Advisory Council, 1986). The report articulated the goal of Earth system science: "to obtain scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may expect to continue to evolve on all timescales." The challenge of this nascent discipline was to develop the capacity to predict those changes that will occur in the next decade to century, both naturally and in response to human activity.

A conceptual model of the Earth system, now known as the Bretherton diagram (Fig. 1a), but developed by Berrien Moore, a future chair of IGBP, saw "human activities" contained within a box on the far right of the diagram. Arrows from boxes marked "climate change" and "terrestrial ecosystems" lead into this box. Arrows leaving this box arrive at "land use", "CO_2" and "pollutants". Over the intervening decades, the position and connections with this box became the focus of considerable discussion as the central roles of human activities were increasingly recognized as agents of change and response in the Earth system (e.g., Consortium for International Earth Science Information Network, 1992; Crutzen and Stoermer 2000; Mooney et al., 2013). This increased recognition is evident throughout the three decades of IGBP, as discussed in this paper, with "humans" increasingly incorporated as essential components in all research and activities.

By September 1986, Bolin's committee reported back to the ICSU General Assembly with the conclusion: "What is called for . . . is a transdisciplinary programme" [emphasis in the original]. Based on the ad hoc planning committee's report, in 1987 the ICSU General Assembly appointed a Special Committee for the International Geosphere–Biosphere Programme—A Study of Global Change (IGBP) chaired by James McCarthy to further advance the planning of IGBP (IGBP, 1987). In 1987, the IGBP secretariat opened in Stockholm at the Royal Swedish Academy of Sciences. In 1988, the president of ICSU Sir John Kendrew said: "IGBP will certainly be the most ambitious, the most wide-ranging and, in its impacts on our understanding of the future possibilities for mankind, the most important project that ICSU has ever undertaken. Its purpose is to study the progressive changes in the environment of the human species on this Earth, past and future; to identify their causes, natural or man-made, and to make informed predictions of the long-term future and thus of the dangers to our well being and even to our survival; and to investigate ways of minimizing those dangers that may be open to human intervention." (IGBP, 1988).

International support grew. For example, in 1987 an International Arctic Global Change Workshop, under the leadership of Jack Eddy and William Fyfe was held (UCAR, Boulder) to ensure that dimensions of Arctic science would have a scientific place within IGBP. The meeting was also instrumental in supporting the launch of the International Arctic Science Council in 1990. In 1989, the United Nations passed resolution 44/207, which recommended that governments "increase their activities in support of . . . the International Geosphere–Biosphere Programme, including the monitoring of atmospheric composition and climate conditions, and also recommends that the international community support efforts by developing countries to participate in these scientific activities."

3. Phase One: understanding individual components of the Earth system

3.1. Broader context

With a certain degree of foresight, IGBP's first report from 1986 states: "If planning starts now, the IGBP can be in operation in the 1990s—a significant period of projected change during which we may expect the first observable climatic impact of concentrations of greenhouse gases" (IGBP, 1986). No one could have predicted the confluence of events that were to unfurl.

The Cold War thawed abruptly in November 1989 with the fall of the Berlin Wall, which cleared the way for an aggressive drive towards greater degrees of globalization and data sharing. For example, the needed U.S. Navy submarine data on ice extent and thickness was released under the leadership of U.S. Vice President Al Gore. While aerial photography and satellite imagery could monitor sea ice extent, only such submarine-collected data was tracking ice thickness. The internet, continuing improvements in Earth observation satellites (Kaye and Downy, 2015) and increasingly powerful supercomputers revolutionized science and expanded research possibilities, all of which were important in the continued evolution of IGBP as a global network of scientists studying the Earth system.

Concern continued to mount about climate change. In his autobiography Bolin says: "Intensified research efforts were needed, and the planning and organisation of these were being taken care of by . . . WCRP . . . [and] . . . IGBP. The key question remained: how should the interactions between the scientific community, stakeholders and politicians that might bring the issue forward politically be developed." Under the auspices of UNEP and WMO, the Intergovernmental Panel on Climate Change was established in 1988. UNEP director Mustafa Tolba invited Bolin to chair the panel, which he did from 1988 to 1997—the period of the first two assessments. Close ties between IPCC and IGBP have continued.

IGBP's long-term planning and organization hinged around process studies, observations, global models, past global change and, finally, global data and communications systems (IGBP, 1986). By 1991, five international projects were underway in IGBP (Fig. 2 and Box 1). Some of these were bottom-up projects developed by various disciplinary communities that were then absorbed by IGBP's growing interdisciplinary network. By 1995, ten projects were active (Fig. 2).

3.2. Science

Understanding the Earth system needs a global perspective of the processes and interactions within and among the Earth's atmosphere, oceans and land linked to regional and local scales (Andreae et al., 2004; Steffen et al., 2004). Fundamental to this was the development of global databases to record the spatial and

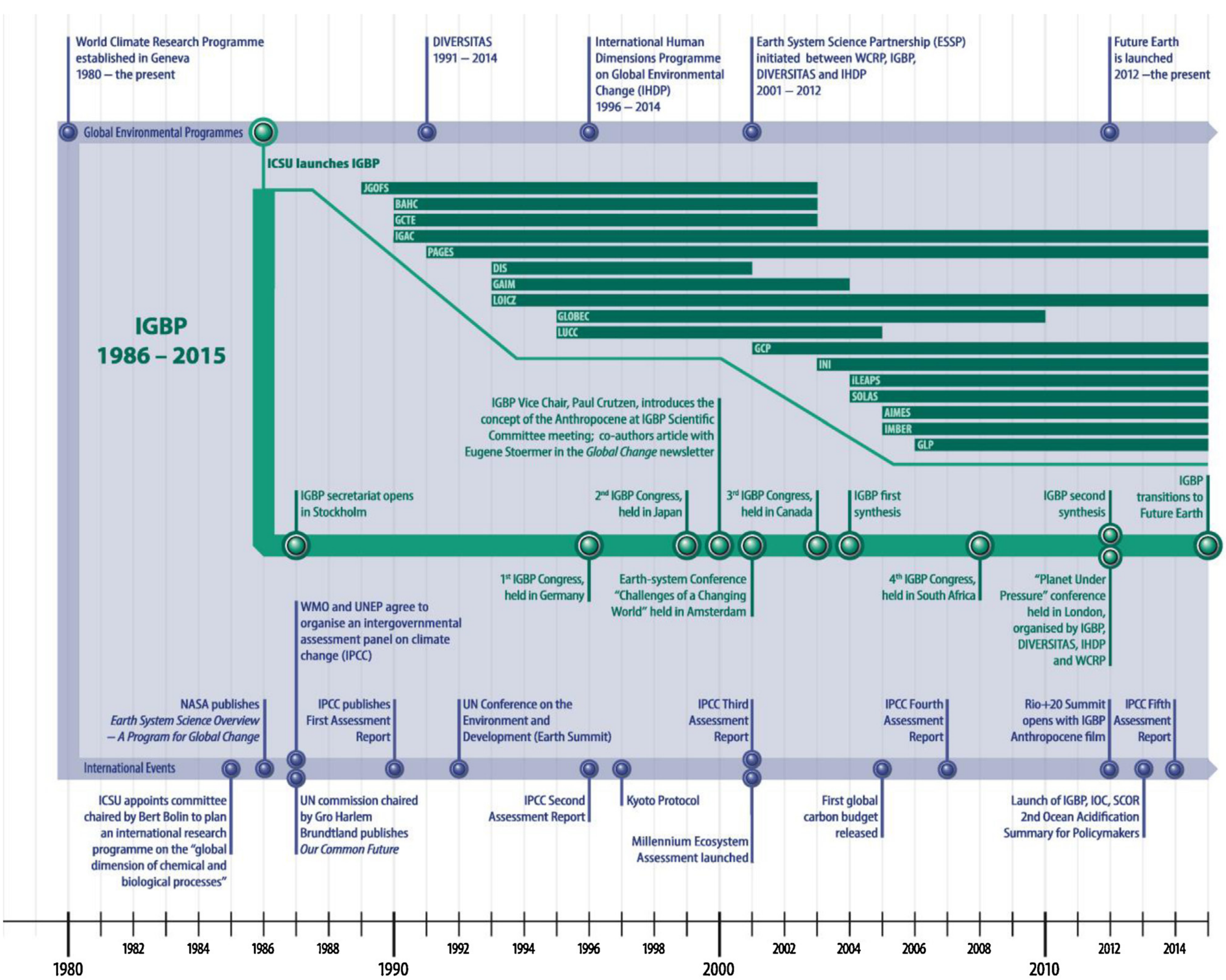

Fig. 2. Timeline of some significant events in the history of IGBP and the global environmental change programs.

Box 1. IGBP projects and their acronyms.

IGBP phase 1	
BAHC	Biosphere aspects of the hydrological cycle
DIS	Data and information systems
GAIM	Global analysis integration and modelling
GCTE	Global change and terrestrial ecosystems
GLOBEC	Global ocean ecosystem dynamics
IGAC	International global atmospheric chemistry
JGOFS	Joint global ocean flux study
LOICZ	Land–ocean interactions in the coastal zone
LUCC	Land use and cover change
PAGES	Past global changes
IGBP phase 2 to present	
AIMES	Analysis, integration and modelling of the earth system
GLP	Global land project
IGAC	International global atmospheric chemistry
iLEAPS	Integrated land ecosystem–atmosphere processes study
IMBER	Integrated marine biogeochemistry and ecosystem research
LOICZ	Land–ocean interaction in the coastal zone
PAGES	Past global changes
SOLAS	Surface ocean lower atmosphere study
Earth system science program projects	
GCP	Global carbon project
GWSP	Global water system project
GECAFS	Global environmental change and food systems
GECHH	Global environmental change and human health

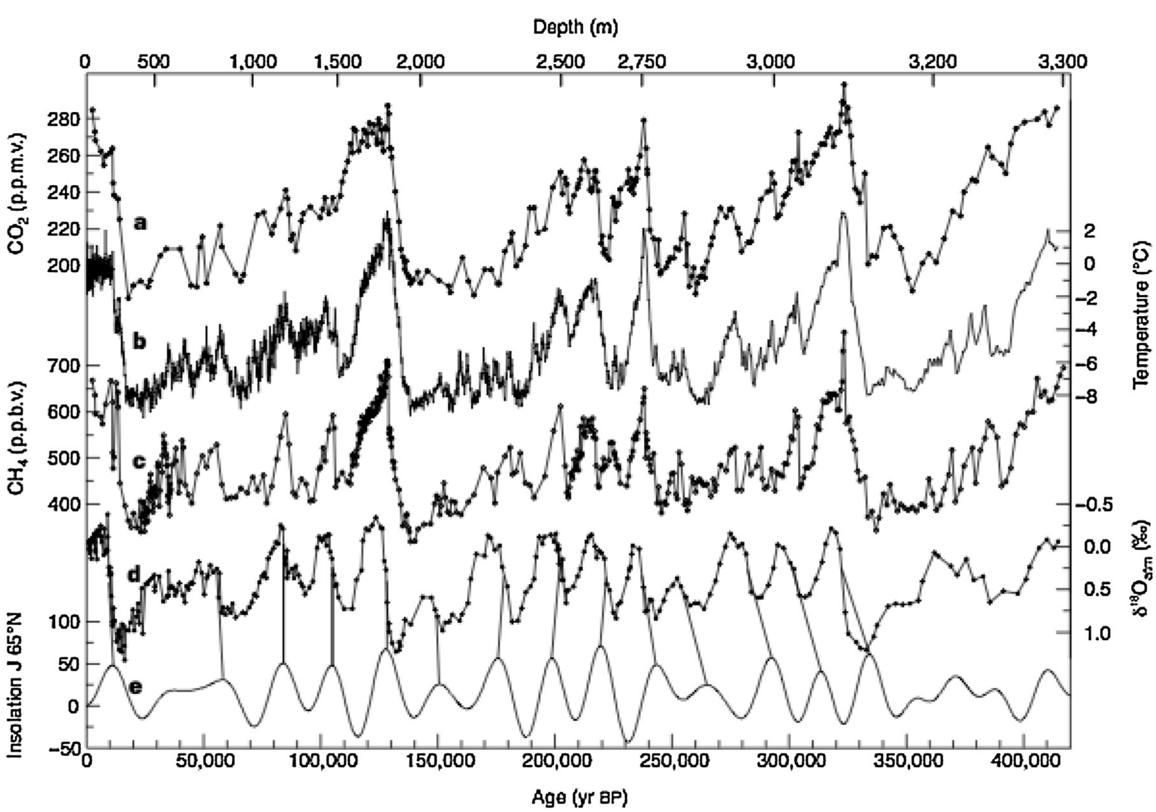

Fig. 3. Glacial–interglacial dynamics of the Earth as a system recorded in the Vostok ice core Reprinted by permission from Macmillan Publishers Ltd: Nature (Petit et al.), copyright 1999.

temporal variation of many key system components. For example, researchers working on the atmosphere in the IGAC core project (Box 1) compiled some of the first global databases of the distribution and emissions of reactive trace species (e.g., N_2O, NO, CH_4, DMS) and aerosols in the troposphere (Brasseur et al., 2003). This was supported by in-situ measurements and air-borne campaigns around the world (Melamed et al., 2015). Meanwhile, using advances in remote sensing technologies (Advanced Very High Resolution Radiometer, AVHRR), IGBP-DIScover developed a global land-cover classification scheme with 17 classes, which were identified on the basis of requirements of the IGBP core projects, and was used to develop global 1 km land cover databases (Belward et al., 1999; Loveland et al., 2000). IGBP-DIS collaborated actively with the United States Geological Survey, NASA, National Oceanic and Atmospheric Administration and the European Space Agency (Belward et al., 1999). The classification scheme continues to be used widely today to assess changes at local to global scales in deforestation, cropland, urbanization and climate change, for example (Goldewijk 2001; McGuire et al., 2001; McCarthy et al., 2012). Synthesis of land cover case studies, developed from an IGBP organized workshop, allowed the identification of common drivers and causation patterns (Lambin et al., 2000, 2001). An automated global network of flux towers (FluxNet) was initiated to measure terrestrial fluxes, with standardized measurements, which are key to understanding global carbon fluxes. The marine projects, JGOFS and GLOBEC, put considerable emphasis on data availability, data archiving and data quality, which resulted in fundamental changes in how data are handled and archived. This has facilitated analysis of global ocean ecosystems and biogeochemical changes in response to climate and anthropogenic changes (e.g., Longhurst 1998). For example, JGOFS made significant advances in mapping the global ocean fluxes of CO_2 (Takahashi et al., 2002) which were critical for understanding the role of the ocean in climate change.

Contemporary conditions were not the only perspective in database development. The land community (LUCC) reconstructed land cover for the past 300 years, motivated in part by the need to contextualize present-day tropical deforestation (Ramankutty and Foley 1999; Ramankutty et al., 2006). New work on ice cores led to major advances in documenting past climate, especially for the late Quaternary Period. For example, ice cores from Antarctica and Greenland led to a detailed record of atmospheric composition (in particular CO_2, N_2O, CH_4,) (Petit et al., 1999; Raynaud et al., 2003) (Fig. 3). For the first time, we had an insight into long-term forcings and response of the climate system, thus allowing us to put the recent, anthropogenic changes in context.

Biology was a crucial component of IGBP science, and it remains so today. When IGBP was launched, research at the Earth system level focused predominantly on the physical dimensions: the role of organisms, ecosystems and biogeochemistry had not been explored sufficiently. Early IGBP projects brought in this element explicitly. For example, plant biodiversity along with climate, water and nutrient availability were found to determine the response of terrestrial plants to elevated CO_2 (Potvin et al., 2007). JGOFS quantified the fluxes of carbon between the ocean and atmosphere, and explored its biological transformation in the ocean and eventual burial in the deep sea. The project highlighted the contribution of the microbial loop in the carbon cycle of the oceans, which previously had been primarily attributed to only phytoplankton and zooplankton (Ducklow et al., 2001). However, the project had little to no focus on food web components or dynamics except as processes to transform organic matter (e.g. zooplankton fecal pellets). GLOBEC in contrast focused on marine

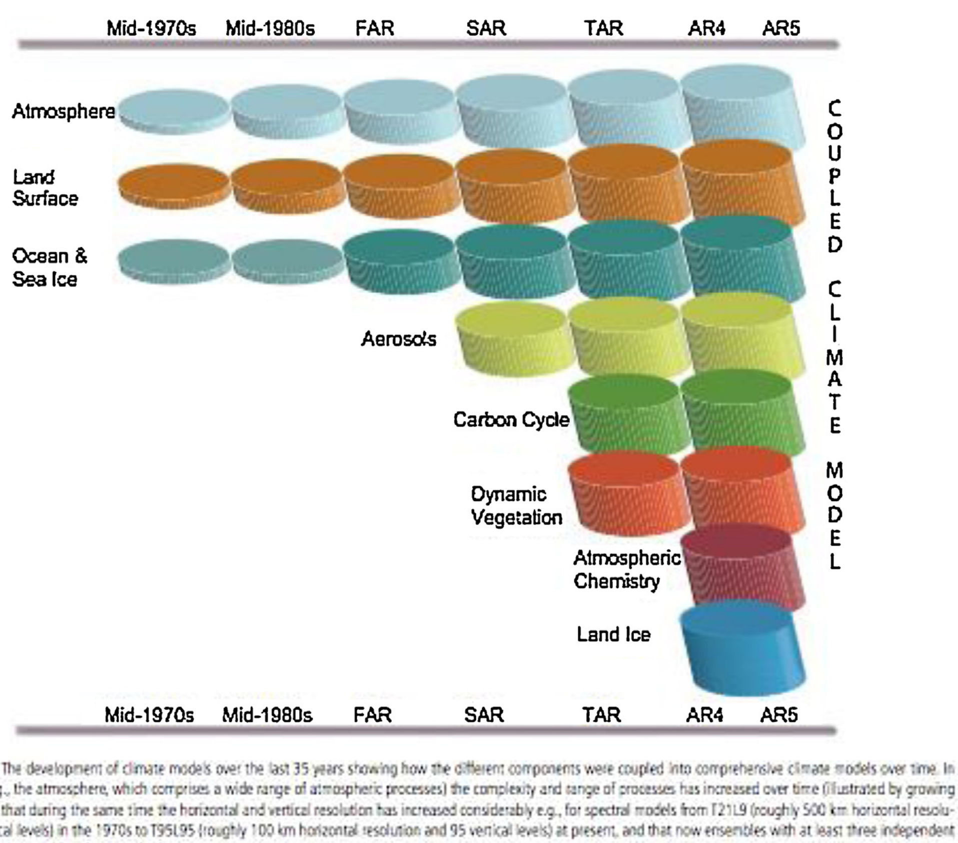

Fig. 4. Development of climate models used in IPCC Assessment Reports showing how different components, including biogeochemical components, were coupled into comprehensive climate models over time (from WG I Fig. 1.13 IPCC AR5).

food web structures and functions, including understanding variability in larval fish recruitment and their response to climate change (Fogarty and Powell, 2002). The projects benefited from their collaborations with space agencies including NASA and ESA in combining satellite observations with a global network of in situ observations (JGOFS, Remote Sensing Team 1996).

Climate change was not a major topic of early research by IGBP and its projects, but this changed by the end of the programme's first decade. As noted above, the cyclic pattern of atmospheric composition and climate over the last four glacial cycles provided unprecedented insights into Earth system response (Petit et al., 1999) and triggered lively discussions at the IGBP Congress in Japan in 1999 (M. Claussen pers. comm.). This led to the initiation of an IGBP workshop on biogeochemical cycling in an Earth system science context (Falkowski et al., 2000) which, according to former Executive Director Will Steffen, "strengthened IGBP's standing on carbon cycle research, and led to discussions with Bert Bolin about how IGBP could contribute to the IPCC." IGBP was instrumental in setting out the basic science of the terrestrial carbon cycle in an IPCC special report on land use, land use change and forestry. The bulk of the writing team for Chapter 1 on the basic science (Bolin et al., 2000) was associated with IGBP although authors were invited in their personal capacities.

Through a combination of process studies and modeling, knowledge of the dynamics of Earth system components and their interactions was developing. IGBP championed the advancement of the biogeochemical components of the land and ocean carbon cycle in the global climate models, which had included primarily the physical components of the climate system in the first IPCC assessment report (1990) (Fig. 4). The IGBP community led a strong focus on independent sub-system analysis of the carbon cycle. This included both model development and model inter-comparisons, which significantly improved the quantification of carbon pools and fluxes, and uncertainties in terrestrial primary production (Claussen et al., 1998; Heimann et al., 1998) and the ocean C cycle (Orr et al., 2001; Doney et al., 2003). For example, the critical importance of feedback processes between terrestrial ecosystems and the atmosphere came to the fore. The large contribution of wetlands and rice paddies to global emissions of methane and of agriculture to global ammonia emissions lead to increased recognition and understanding of biosphere–atmosphere interactions and their contribution to global tropospheric composition (Scholes et al., 2003). Terrestrial ecosystems were indicated to be important determinants of the water cycle and the trajectory of atmospheric carbon-dioxide concentrations, and thus climate change, over the coming few decades and centuries as highlighted by BAHC (Kabat et al., 2004). Several research groups associated with GCTE produced prototype dynamic global vegetation models (DGVMs) by the mid-1990s, with model intercomparisons implemented later in the decade (Cramer et al., 2001). DGVMs were beginning to be recognized as an essential component – as important as the oceans and the atmosphere – in Earth system models. Many of the advances discussed above, combined with parallel scientific and technological developments, helped to later develop dynamic models of the Earth system and its interacting components.

Researchers working at the land-ocean interface in LOICZ developed a global perspective of the link between land and coastal ocean biogeochemistry, which included the controlling role of human populations and runoff. This involved measurements and modeling in over 150 sites around the world of river nutrient fluxes (dissolved inorganic N and P) to (Smith et al., 2003), and biotic and non-biotic transformations within, the coastal ocean (Smith et al., 2005).

A salient feature of phase 1 was the facilitation of international collaboration and the coming together of multiple disciplines. For example, an emerging international community of atmospheric chemists engaged biologists, ecologists, biogeochemists and others to further understand the role of atmospheric processes in the Earth system (Brasseur et al., 2003). In the ocean domain, physical, chemical, biogeochemical and biological oceanographers began working with microbial ecologists and fisheries biologists (Wiebe et al., 2001; Le Borgne et al., 2002; Fasham 2003). Hydrologists, meteorologists and biologists began working together more closely which lead to a new perspective that vegetation does matter in climate and weather (Kabat et al., 2004). Furthermore BAHC started to involve the human dimension by promoting integrated water resource management and a new vulnerability concept.

3.3. Outlook

By the end of the 1990s, the programme's research communities had built up a substantial body of knowledge, laying the foundation for major syntheses from each core project (Alverson et al., 2003; Brasseur et al., 2003; Fasham 2003; Kabat et al., 2004; Crossland et al., 2005; Lambin and Giest 2006; Canadell et al., 2007a). These constituted an IGBP book series and while many were published in early 2000s they synthesized phase 1 of IGBP. We came to know much more about individual components of the Earth system than we did when IGBP began and knowledge was building of the interactions among the Earth system components. The interaction between IGBP and IPCC increased and many scientists associated with IGBP were invited to author teams on special reports or chapters and some IGBP achievements contributed directly to IPCC's first two assessments. We also attained greater certainty about the nature and intensity of human impacts on Earth's climate and environment. Time was ripe for a major programme-wide synthesis that would allow a more complete picture to emerge.

4. Phase 2: humans as components of the Earth system

4.1. Broader context

The late 1990s and early 2000s were a period of intense intellectual churning at IGBP. The scientific leadership was keenly aware of the need for a programme-wide synthesis to complement project-level syntheses that had already begun. At the scientific committee meeting in 1999, ecologist Pamela Matson, on behalf of an ad hoc Integration Overview Group, presented an outline of the proposed synthesis including the dynamics of the Earth system, how humans are changing the system and the how the response, consequences and risks of those changes to the system unfold (Minutes of the 14th IGBP SC meeting). Opinion pieces in the IGBP *Global Change* newsletter further elaborated on the timeliness and rationale of the synthesis (see for example Moore, 1999; Steffen 1999; Swanberg 1999).

The community was also beginning to have a greater appreciation of the degree to which humans had altered and were continuing to alter their environment—in fact, the Earth system as a whole. Indeed, the "Anthropocene" finds mention in the minutes of the scientific committee meeting in 2000. Soon afterwards Paul Crutzen, then IGBP Vice-Chair, and Eugene Stoermer introduced the concept to the wider community via an article in the IGBP *Global Change* newsletter (Crutzen and Stoermer, 2000). In part through Crutzen's senior leadership role in IGBP, the concept rapidly became used throughout IGBP as its core projects developed their individual syntheses, and it featured prominently in the programme-wide synthesis, which sought to quantify it by means of the Great Acceleration graphs (Steffen et al., 2004; Steffen, 2013).

An example of how fast this Anthropocene concept penetrated the scientific community was to be found during the first meeting of the IGBP Water Group held in Boulder, 2000. With IGBP sponsorship and representatives from LOICZ, PAGES and BAHC, the meeting explored how “Anthropogenic influences and changing climate can (both) affect the “normal” supply and flux of sediment along hydrological pathways” (Syvitski 2003). This competing influence of human action at the local scale versus human action at the global scale has become a major theme in most of the geoscience communities.

Around the same time, IGBP was thinking about a new organizing principle for its research. Discussions at the scientific committee meetings in 2000 and 2001 revolved around the need for a more integrated approach to the Earth system. A paper emerging from these discussions identified, among other things, the challenge of achieving “effective synergies between the synthesis and analysis modes” of understanding the Earth system (Appendix to the 16th IGBP SC Meeting minutes 2001). Eventually, this brainstorming led to a revised structure in phase 2 of IGBP in which core projects – older ones as well as newly launched ones – conformed to either individual components of the Earth system or the interfaces between them (Fig. 1b). The 3rd IGBP Congress “Connectivities in the Earth System” organized in Banff (June 19–24, 2003) provided an opportunity to review the new directions for the second phase of the programme and to discuss how to best implement them. Congress participants recognized that “IGBP must identify the vital elements and functions of the Earth System that can be transformed by human activities, and determine the tolerable and the intolerable domains for humans in the Earth System.” (Brasseur 2003).

The IGBP community was keen to forge closer relationships with its sister global-change programmes—The World Climate Research Programme (WCRP), DIVERSITAS (formed in 1991) and the International Human Dimensions Programme on Global Environmental Change (IHDP) (formed in 1996). The desire to create an “Integrated Earth System Science Programme” (Minutes of the 2000 IGBP SC Meeting) would eventually culminate in the launch of the Earth System Science Partnership (ESSP) and joint projects. The formation of ESSP (in 2001) meant that carbon, water, food security and health (Box 1) would now be looked at by projects sponsored jointly by the four global-change programmes. IGBP recognized the importance of closer interaction between natural and social scientists, and IHDP became a co-sponsor of two of its projects (GLP and LOICZ).

The global change open science conference, held in Amsterdam in 2001, was a key event at the beginning of IGBP’s second phase. The conference, organized by IGBP in association with its sister global-change programmes, highlighted their research achievements, as well as the emerging outcomes of IGBP’s first synthesis. It also explored the pathway that Earth system science would take in the following decade. The conference is perhaps best remembered for the “Amsterdam Declaration”, which stated unequivocally that anthropogenic forces were “equal to some of the great forces of nature in their extent and impact.” (Moore et al., 2001). Furthermore, the declaration calls for “an ethical framework for global stewardship and strategies for Earth system management.” Uhrqvist (2014a,b) interprets this declaration as highlighting the Earth system as the central object of knowledge and global governance.

4.2. Science

Research during the second phase responded to the growing recognition that humans were the prime driver of change on the planet. Understanding the Anthropocene required a more integrated approach to the Earth system and thus greater emphasis on interdisciplinarity. This interdisciplinarity was reflected both within a core project as well as in increased interaction among core projects. The human dimensions were brought in more explicitly and there was more engagement with stakeholders. Climate became a more prominent component of many core projects’ scientific agendas.

Interdisciplinarity was a key design feature of the new Global Land Project (GLP). Scientists across the social, economic, geographical and natural sciences were engaged to address changes in the land system and the dynamic interaction between socioeconomic and biophysical drivers of that change. An analysis of land acquisitions in Africa by China and other countries highlighted the extent to which food production systems and decision making are increasingly spatially disconnected from their natural resource base as well as from the demand side of the production chain (i.e. the socio-economic drivers) (Friis and Reenberg, 2010). A global analysis of the extent to which humans appropriate terrestrial net primary production (HANPP) provided the first global measure of the reduction of trophic (=food) energy available for all other species than humans and their livestock (24% of global terrestrial net primary production) (Haberl et al., 2007). Further studies related the contribution of socio-economic activities to HANPP, thus providing information that could inform preventive measures to lower human pressures on ecosystems (Erb et al., 2009).

In 2002, a community of ‘nitrogen’ scientists, industry representatives, governments and practitioners organized under the banner of the International Nitrogen Initiative (INI) that became the first Fast-Track project of IGBP. The overarching goal was to “optimize nitrogen’s beneficial role in sustainable food production and minimize its negative effects on human health and the environment resulting from food and energy production” (Erisman et al., 1998). A preliminary global assessment of nitrogen fluxes and issues highlighted the need for interconnected regional to global approaches across a range of actors (Galloway et al., 2004). Communication tools were developed to help raise political and societal awareness about the feedbacks between the biogeophysical and society forcings and responses. For example the Nitrogen Visualization Tool is an online interactive tool that allows users to investigate the consequences of changing food patterns or using more fossil fuels on the environment or the hunger in the world (www.initrogen.org).

The contribution of IGBP to IPCC was explicitly acknowledged in the Fourth Assessment Report. “This assessment has benefited greatly from the very high degree of co-operation that exists within the international climate science community and its coordination by the World Meteorological Organization World Climate Research Programme (WCRP) and the International Geosphere Biosphere Programme (IGBP)” (Pachauri et al., 2004). Climate change continued to rise on the agenda of many core projects. Looking towards the IPCC Fifth Assessment Report, in 2007 an integrated workshop brought together a range of different modelling communities (climate, chemistry, carbon cycle, terrestrial, land-use), as well as social scientists working on emissions, economics, policy, vulnerablity and impacts. AIMES was an important contributor to the outcome which was a new strategy for the next-generation of climate simulations using the greenhouse-gas emissions pathways, the Representative Concentration Pathways or RCPs, which became the foundation of model experiments for AR5 (Hibbard et al., 2007; Moss et al., 2010; Van Vuuren et al., 2011). The Global Carbon Project (GCP) released their first global carbon budget in 2007 (Canadell et al., 2007a,b) with annual updates since then of new advances in understanding and constraining the human perturbation of the carbon cycle (Le Quéré et al., 2009, 2015).

By the mid-2000s ocean acidification came to the fore as an important global-change issue as biologists became wise to its potentially negative effects on many species of shelled organisms and corals, and therefore potentially negative implications for fisheries and society (Orr et al., 2005; Riebesell et al., 2008). The topic was attracting the attention of the PAGES community too, which led an IGBP- and SCOR-sponsored fast-track initiative to analyze past analogues that might help elucidate the nature and impacts of modern ocean acidification (Ridgwell and Schmidt, 2010).

Studies on climate change in the context of multiple stresses increased. For example, IGAC focused on the connection between air pollution and climate (Monks et al., 2009; Stohl et al., 2009). LOICZ, along with partners such as the Arctic Council, developed a comprehensive picture of the status as well as the current and anticipated changes due to climate and other stresses in the most sensitive Arctic coastal areas (Forbes et al., 2011). The project also looked at deltas as hotspots of change. An analysis of 33 deltas around the world concluded that the overwhelming majority are sinking, often due to a multitude of stresses including decrease in sediment load, urbanization, water and mineral mining, land-use change and damming in watersheds, in addition to rising sea level from climate change (Overeem and Brakenridge 2009; Syvitski et al., 2009).

The land-atmosphere community represented by iLEAPS elucidated the role of local and regional factors that exacerbate climate extremes. For example, land cover was found to play a key role in the regional extent of extreme heating during the 2003–2006 European heat waves (Teuling et al., 2010). Regions with grassland experienced higher maximum temperatures than those with forested areas, which was attributed to soil-moisture deficits in the former areas.

Meanwhile, the new community working at the interface of the oceans and atmosphere (SOLAS) turned its attention to climate-relevant gases such as CO_2, N_2O and dimethyl sulphide (DMS) in addition to impacts of atmospheric material (iron and nitrogen) supply. Increasing collaboration developed among oceanographers, atmospheric scientists, chemists, biologists and physicists. Coupled with new techniques and new generations of chemical sensors uncertainties were reduced in our understanding of the biogeochemistry of the air-sea interface, the exchange of materials at this interface, and the development of better models (Jickells et al., 2005; Johnson 2010; Fairall et al., 2011). An interdisciplinary workshop, co-sponsored by SOLAS and bringing together the atmospheric and oceanographic communities, estimated that the impacts of atmospheric anthropogenic nitrogen deposition on the open ocean was now reaching levels similar to biological N_2-fixation with implications for net primary production (Duce et al., 2008). Recognition of the important role of iron as a limiting nutrient of primary production in some ocean regions (Martin and Fitzwater, 1988; Le Borgne et al., 2002) led to more explicit consideration of nitrogen, silicon, phosphorus and iron cycles in some of the global ocean biogeochemical models used by the IPCC. Interest in fertilizing the oceans surface waters with iron or other nutrients to potentially increase the biological carbon pump as a means of climate engineering, prompted IOC-UNESCO to commission SOLAS to prepare a summary of the scientific understanding for policy makers on Ocean Fertilization (Wallace et al., 2010).

All of this research collectively contributed to advancements in regional-to-global models, including enhancements of interconnections between sub-systems of the Earth System. For example, Earth system models were making important advances in incorporating carbon cycle feedbacks to the climate system (Friedlingstein et al., 2006; Ciais et al., 2014) and the dynamics of terrestrial ecosystem-atmosphere exchange processes (Seneviratne et al., 2006; Pitman et al., 2009; Ganzeveld et al., 2010). End-to-end models linking ocean biogeochemistry to food webs were emerging (Fulton, 2010) and continued to advance in phase three (Ruzicka et al., 2013). Simplified formulations of Earth system dynamics over paleo time frames were developed using EMICs (Earth System Models of Intermediate Complexity) (Claussen et al., 2002), and through GAIM the EMIC community flourished. Many of the model developments involved close collaboration with WCRP and other partners.

4.3. Outlook

By the end of the first decade of the 21st century, the Anthropocene concept was well endorsed by the IGBP community. Projects were organized based on a new view of the Earth system and the human dimensions were brought in more explicitly. Climate science and the interaction with the IPCC and UNFCCC continued to gain greater prominence. Numerous products aimed at communicating science to decision makers were developed.

In 2009, the ICSU and the International Group of Funding Agencies (IGFA) published their review of IGBP (ICSU-IGFA, 2009). The review team, while acknowledging the programme's significant contributions to science and policy, recommended that IGBP maximize its impacts on science, policy and practice. The team emphasized that "in setting future scientific priorities within IGBP-related activities, finding solutions to practical problems must feature much more strongly than IGBP has hitherto been mandated."

The review also alluded to the increasingly more complex landscape of global-environmental-change research. Noting the "increasingly unwieldy and confusing arrangements among the Programmes, and between them and ESSP", the review team stated that "most people contributing evidence to this review do not believe that there should be four GEC Programmes with independent planning a decade from now." ICSU initiated a process of "Earth system visioning". The goal was to develop a ten-year effort to address challenges in global sustainability research.

In 2010 IGBP revised its vision statement calling for increased societal relevance, and increased integration across the natural-social science and policy domains (www.IGBP.net). IGBP continued to actively engage scientists from developing countries and countries in economic transition in all its committees, projects, workshops and other activities.

This combination of events and circumstances—IGBP's internal assessment in 2007 (22nd IGBP SC minutes) and subsequent revised vision, ICSU/IGFA's review and visioning process, changes in the funding landscape and even the growing frustration with the lack of action on climate change—propelled IGBP in the direction of enhanced interaction with policy, greater emphasis on communication and a focus on solutions and sustainability in phase three. The Anthropocene concept framed an increasing number of activities. Throughout IGBP there was an effort to deepen the engagement of social scientists. New scientific findings were still being published, but there was an increasing demand for demonstrating their relevance for solving societal issues. The projects began revising their science plans to address the growing emphasis on policy relevance, stakeholder engagement and co-design and co-production. A new era was developing in international coordination: the new Future Earth initiative.

5. Phase three: towards sustainability

5.1. Broader context and science

In phase three, IGBP has continued to study Earth system processes, but with an increased emphasis on the applicability and relevance of this knowledge. It called on the UN to take a more integrated view of its over 500 international treaties and conventions that address the environment (Seitzinger 2010). It invested substantially on communication and the science-policy interface, targeting processes such as Rio + 20, the Convention on Biological Diversity (CBD) and the UN Sustainable Development Goals (Griggs et al., 2013), in addition to the ongoing emphasis on the UN Framework Convention on Climate Change (UNFCCC) and IPCC. It produced numerous policy briefs (IGBP, IOC, SCOR, 2009, 2013; www.IGBP.net) and, in particular, helped to raise the profile of ocean acidification in policy arenas via conferences, and through engagement in the International Ocean Acidification Reference Users Group (IOA RUG). It moved knowledge from the academic arena to the public through user-friendly tools, such as the Nitrogen Footprint Calculator that allows individuals and institutions to calculate their nitrogen footprint, their activities that are impacting it, and insights in how to reduce their N footprint (www.nprint.org) (Leach et al., 2012; Galloway et al., 2014). It worked closely with the Global Carbon Project to ensure that the findings of its annual carbon budget were communicated as widely as possible.

In 2010 IGBP initiated the planning of the second major global-change conference, *Planet Under Pressure*. It was the largest and most ambitious conference and had the broadest engagement strategy in IGBP's history. The IGBP secretariat, along with partners, made an unprecedented effort to bring together diverse communities of scientists, policymakers and practitioners from across the world for the conference, which was held in London in 2012 with over 3000 participants on-site and an additional 3000 online. This community would provide the nucleus for Future Earth, the new initiative on global sustainability (Future Earth, 2013). Addressing the conference, UN Secretary-General Ban Ki-moon said he was ready to work with the scientific community on the new initiative. As with the Amsterdam Conference, *Planet Under Pressure* also led to a declaration—the State of the Planet Declaration (www.IGBP.net). Recognizing the rapid and global scale of change in the planet's inter-related social, economic and environmental systems, the declaration called for "a new approach to research that is more integrative, international and solutions-oriented" The conference raised some difficult challenges too, particularly for traditional Earth system scientists, which were summarized by the late Mike Raupach in his article for the *IGBP Global Change* magazine (Raupach 2012). Given the incomplete knowledge about changes and drivers in the Earth system, the importance of addressing equity and differing values, and the high stakes and urgency for action, Raupach noted that it is "no longer possible for Earth-system science to remain 'value-free' and detached from policy."

In 2010, IGBP launched a synthesis on specific topics. This differed from the IGBP programme-wide synthesis in the early 2000s, in both scope and approach. It focused on specific emerging topics identified not only by IGBP's scientific committee, but with input from key stakeholders, including other international research programmes and IPCC. Furthermore, the synthesis sought to involve scientists from many disciplines outside of IGBP as well as policymakers and other stakeholders. This broader engagement in the identification and development of topics was evident in the outcomes which contributed to, for example, the increased focus on the links between nitrogen and climate for IPCC's AR5 (Erisman et al., 2011); a review on the ecosystem impacts of geoengineering (Russell et al., 2012); and an assessment of the socioeconomic consequences of, and responses to, global environmental change in least developed countries (Dube and Sivakumar, 2015). The synthesis topic exploring the links between air pollution and climate was further expanded to a multidisciplinary initiative in IGAC on the links between air pollution, health and climate (Melamed et al., 2015).

Many core projects undertook additional syntheses on specific topics. Urban regions around the world were the focus of a major synthesis of atmospheric pollution data (Zhu et al., 2012). Recognizing the continuing negative consequences for human health and ecosystems, IGAC initiated the first global assessment of tropospheric ozone. PAGES undertook a major synthesis to document the temperature and precipitation history of various regions of the world during the past two millennia (PAGES-2k Consortium, 2013). SOLAS, along with the International Ocean Carbon Coordination Project (IOCCP), continued development of global databases for surface-water CO_2 distribution and DMS emissions: these were used for model-data comparison and for better quantification of the ocean carbon sink and to understand how it varies with location and in time (Bakker et al., 2014). Given the many different climate and Earth system models being developed, a critical activity in preparation for IPCC AR5 was the intercomparison of models (MIPs) that increased understanding of uncertainty across the range of climate and Earth System models (Brovkin et al., 2013; Sailley et al., 2013; Shindell et al., 2013). The model intercomparisons involved close collaboration with WCRP and other partners.

Understanding of the feedbacks between the biogeophysical and societal forcings and responses continued to grow. Environmental forcings and management response provided insight into the different patterns of collapse and recovery of the cod fisheries off Labrador, Newfoundland and the Barents Sea (Norway–Canada Comparisons of Marine Ecosystems-IMBER NORCAN project) (Lilly et al., 2013). Climate-driven favorable environmental conditions combined with timely responses by fishery managers were shown to have allowed the Barents Sea cod stock to recover and rebuild while the collapse of the cod stock off Newfoundland and Labrador suffered from high mortality due to poor environmental conditions and the slow response to reduce fishing pressure.

The Anthropocene and notions such as teleconnections continued to rise in importance. Within the GLP community researchers began to pay increasing attention to feedbacks between drivers and impacts, adaptive behavior, the interactions between social and ecological systems, and teleconnections between world regions, cities and their rural hinterlands (Lambin and Meyfroidt, 2011; Seto et al., 2012; Liu et al., 2013). Planetary Stewardship in the Anthropocene, a workshop initiated by the IGBP secretariat, brought together natural and social scientists as well as experts from the UN and the World Bank. The focus on urbanization and urban-rural teleconnections highlighted the central role of a system of cities in promoting global sustainability (Seitzinger et al., 2012).

Changes in the global-change institutional landscape meant that concepts such as co-design and co-production of knowledge came to the fore prominently during Phase Three. GLP began building a knowledge base on co-production/co-design in land change science (GLP Newsletter 2015; Verburg et al., 2015). LOICZ continued promoting collaborative research between natural and social sciences and developed conceptual frameworks for managing the socio-ecological dynamics of coastal ecosystems (Glaser et al., 2012) and for assessing governance dimensions of ecosystem change. In response to call from policymakers, IGAC – in collaboration with WCRP's SPARC project – undertook a major synthesis on the climate effects of black carbon. That study identified black carbon as the second most important climate forcer after CO_2, as well as highlighting the vast complexity of co-emitted climate-forcing pollutants in reaching that estimate (Bond et al., 2013). INI continued to promote synthesis on the environmental and societal issues surrounding nitrogen and to develop communication tools in collaboration with stakeholders to help raise political and societal awareness. The European Nitrogen Assessment is the result of such a collaboration as was the formation of the Task Force on Reactive Nitrogen under the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution (UNECE CLRTAP) (Sutton et al., 2011), followed by the global assessment, Our Nutrient World, in 2013 (Sutton et al., 2013; http://initrogen.org/index.php.publications/our-nutrient-world/). Through partnerships with boundary organizations, such as the WWF, they have produced a science brief to reach out to the large WWF network (Erisman et al., 2015). IMBER's Human Dimensions Working Group developed an integrated assessment framework that builds on knowledge learned from past experience of responses to global change (Bundy et al., 2015). This enables decision makers, researchers, managers and local stakeholders to evaluate where to most effectively allocate resources to reduce vulnerability and enhance resilience of coastal people and communities to global change.

In 2012 IGBP initiated its final synthesis. The foundation of IGBP, its core projects, developed syntheses documenting their history and accomplishments and including a forward look as they prepared to move into Future Earth (Suni et al., 2015; Brévière et al., 2015; Hofmann et al., 2015; Melamed et al., 2015; Verburg et al., 2015, Schimel et al., 2015, Ramesh et al., 2015). The current paper aimed to demonstrate the significant role IGBP, through the combined work of its core projects and programme level initiatives, played in the evolution of Earth system science through development and international coordination of scientific knowledge on biogeophysical changes to the Earth system and through close interactions with international bodies, such as IPCC, to communicate this science. The Anthropocene featured prominently in the final IGBP synthesis through a suite of papers being published as a special issue in *Global Environmental Change.* Those papers seek to take our understanding of the Anthropocene concept beyond its biophysical confines as they bring to bear various perspectives, from complex-systems theory to governance, on the concept and aim to facilitate a more nuanced understanding (Bai et al., in press; Biermann et al., in press; Brondizio et al., in revision; Verburg et al., in press). The Great Acceleration graphs also were updated as part of the final IGBP synthesis and the changes since 1950 were broken down into those attributable to OECD and non-OECD countries (Steffen et al., 2015).

5.2. Outlook

Looking back over the past almost three decades of IGBP, a reflective question is, has IGBP evolved as envisioned by its founders? The ideas at that time were innovative, ambitious and brave calling, for example, for "interactions between the physical and biological worlds and humanity" (Malone, 2014), bringing together the components of the Earth system into a more integrated understanding (IGBP, 1986), understanding of past and future changes on Earth from natural and human causes . . . ." and to investigate ways of minimizing those dangers" (Sir John Kendrew, IGBP, 1988), and important contributions of science from IGBP to the IPCC assessments (Bolin, 2008). To reflect on some of these challenges we draw on the current overview paper, core project synthesis papers in this volume, and previous IGBP syntheses referred to in this paper. Throughout its three decades IGBP built new international networks, engaging thousands of scientists from developed and developing countries. Beyond the global reach, a key aspect of these networks was that they brought together disciplines that traditionally did not work together (e.g., atmospheric chemistry with biology, ecology, and biogeochemistry) leading to the development of a more integrative understanding of the Earth system, including past and potential future changes. Creation of new global databases, process studies and advances in Earth system modeling from IGBP projects were a foundation upon which new knowledge of the dynamics of the Earth system components and their interactions were built. One indication of the impact of IGBP is that in the last five years at least 144 papers were published in the *Nature* group alone from core project and programme level initiatives (IGBP Annual Reports 2010–2015; www.IGBP.net). The central and increasingly dominant role of human activities as agents of change and response in the Earth system was codified by IGBP in the concept of the Anthropocene.

IGBP's contributions were not limited to the scientific domain; over time its contribution to policy processes grew. Summaries for policy makers of emerging issues (e.g., ocean fertilization, atmospheric chemistry), some of which were directly requested by policy makers and UN organizations, were developed. The substantial scientific input of IGBP core projects and programme initiatives to IPCC assessments were specifically acknowledged in a number of the assessment reports (Bondre and Seitzinger, 2015). IGBP, through its key contributions to the IPCC process can, arguably, take some credit for the scientific foundation upon which the landmark agreement was made by world leaders at the 21st Conference of the Parties (COP 21) of the United Nations to hold global warming to well below 2 °C above preindustrial values (FCCC/CP/2015/L.9).

The original goals of IGBP remain at least as valid today as they were three decades ago. However, much has changed in the world. The world has witnessed a massive globalization of the economy, technological advances, increased resource use, population increases with increasing affluence for many and at the same time a widening of economic disparity. The Anthropocene lens brings forth the interconnections among various social and ecological processes. The new epoch's challenges warrant even closer interaction among various disciplines as well as stakeholders, and even greater engagement of developing countries, than IGBP was able to accomplish. New models for how science is done, communicated and used will be required. This, in part, provides the rationale for Future Earth (2013). Its success will depend on the extent to which funders and existing, focused research communities such as IGBP's core projects are able to buy into and adapt to the new model.

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