CHAPTER 3

CONVERGENCE PLATFORMS: EARTH-SCALE SYSTEMS

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Earth-scale systems have many forms, and all are dynamically interrelated. Environmental Earth-scale systems include the global atmosphere, geological systems, Earth–Sun and space interactions, Earth electric and magnetic fields, nitrogen cycles, climate patterns, ocean currents, regional biodiversity and regional freshwater systems, minerals, water, and energy resource distributions on Earth (Figure 3.1). The global production and consumption of energy can be considered as a separate Earth-scale system that is intimately tied to the global environment. Various man-made technological systems have the requisite scale and scope to be considered Earth-scale, from the global telecommunications system to massive infrastructure systems that serve major metropolitan areas and span nations and continents. For the purposes of this discussion, humanity’s exploration and exploitation of space also falls within the purview of this chapter.

Maintaining the health of Earth-scale systems is a constant and seemingly growing challenge. The global environment continues to suffer from a plethora of changes and risks, from astronomical events and climate change to human activities and widespread species extinction. Pollution, land use change, and over-exploitation are combining to diminish the benefits that Earth’s ecosystems can provide to humanity (Burkhard, Petrosillo, and Costanza 2010). Water is in short supply worldwide, and the availability of potable water is decreasing at the same time as population and per-capita usage is increasing (IWMI 2007; UN-Water 2013). By 2025, water scarcity will have spread further; India and China will continue to be the largest countries facing water stress, and a number of countries in Africa and the Middle East will face extreme water scarcity (Grail Research 2009). Poor water quality and food imbalances adversely impact human health across the globe (Pimentel and Pimentel 2006). The expansion of the world economy is accelerating the consumption of nonrenewable resources such that peak consumption of oil (Deffeyes 2012), natural gas, coal (Maggio and Cacciola 2012), rare earth minerals (Cherry 2011), and even phosphates may all be reached within this century (Clabby 2012). Dealing with these and other Earth-scale system problems is complicated by many factors, including aging populations and rapid urbanization. Also complicating this task is that most Earth-scale systems are intrinsically dynamic, nonlinear, quite sensitive to natural and human perturbations, and interrelated in very complicated fashions.

This chapter explores the relationships between Earth-scale systems and converging technologies, which are broadly defined to include the “NBIC” technologies: nanotechnologies, biotechnologies, information technologies, and cognitive technologies (Roco and Bainbridge 2003), plus derivative advanced technologies (e.g., many that compose the global energy system) that together may be termed “NBIC2” technologies or, broadly, converging knowledge and technology for society (CKTS). Earth-scale systems can encompass converging technologies (e.g., the global energy system

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1For the institutional affiliations of chapter authors and contributors, please see Appendix B, List of Participants and Contributors.
Figure 3.1 Depiction of the global nitrogen cycle on land and in the ocean (Gruber and Galloway 2008; © Nature Publishing Group, used by permission).
encompasses various components built on nanotechnology advances; can be studied using converging technologies (e.g., simulating the Earth’s climate with supercomputer-based global climate models); and/or can be managed using a convergence of technologies (e.g., through geo-engineering). In this chapter, we consider Earth-scale systems from five viewpoints: knowledge systems, monitoring systems, communication systems, management systems, and Earth-scale and other contributing technologies:

- **Knowledge Systems**: These systems are related to how we gain knowledge about Earth-scale systems. Thus, falling within this rubric are specific methods of investigation, data resources, and theoretical frameworks for conceptualizing Earth-scale systems (e.g., as complex, nonlinear systems). It can be argued that a global knowledge network ties all this together.

- **Monitoring Systems**: These systems collect and process data about the Earth-scale systems. These systems also facilitate the measurement of Earth-scale systems. Components of these systems include satellites, sensors, telescopes, gauges, Internet-based traffic information systems, experiments, and social science surveys.²

- **Communication Systems**: These systems provide the physical infrastructure for communications involving the knowledge networks and monitoring systems. These systems encompass human–system interfaces needed to support Earth-scale science and policymaking. These systems also facilitate communication with the public.

- **Management Systems and Tools**: This perspective encompasses those things needed to manage Earth-scale systems. Thus, included here are systems to control Earth-scale systems (e.g., geo-engineering of the global environmental system; Kintisch 2010; Victor et al. 2009); technologies to ameliorate negative aspects of Earth-scale systems (e.g., scrubbers on fossil fuel power plant smoke stacks); and institutions (including organizations, incentives, international agreements) needed to manage Earth systems.

- **Earth-scale and other contributing technological systems**: The Earth-scale technological systems that receive the most attention in this chapter include the global energy production and consumption system; the worldwide telecommunications system; major urban and national infrastructure systems (e.g., roads, bridges, ports, canals, electricity transmission systems, waste and storm water systems, subways, railroads, airports); and humanity’s efforts in space. An important contributing technology that links to other chapters of this report is robotics.

Using this framework, this chapter puts forth a vision of Earth-scale systems and converging technologies, documents advances made in the last ten years, proposes goals for the next decade, discusses infrastructure and R&D strategies to achieve these goals, and sets out priorities. Relationships with other convergence platforms discussed elsewhere in this report are also addressed. The chapter concludes with a set of case studies and examples.

### 3.1 VISION

#### 3.1.1 Changes in the Vision over the Past Decade

The last ten years have witnessed the historically unprecedented growth in science and exponential technology change. If anything, the vision for science and technology’s contributions to solving difficult societal problems has become stronger during this time period as the problems have become worse and as political systems around the world have struggled to find institutional solutions to the problems.

² One example in the field of climate science and sustainability is SNOTEL, a weather-related automated or telemetered monitoring system of weather stations that serves as a snowfall depth monitoring network (established by the USGS; see Trimble, Santee, and Neidrauer 1997). Another is NSF’s NEON observatory designed to gather and provide ecological data on the impacts of climate change, land use change, and invasive species on natural resources and biodiversity.
This vision is especially strong with respect to Earth-scale environmental, energy, and infrastructure systems. Technological solutions to simultaneously solve the world’s energy problems while reducing greenhouse gas emissions are given exceptional credence. This is due in part to spectacular technological change that has impacted the daily lives of almost every human on Earth. Advancements in science—in nanotechnology and biotechnology in particular—are seen as playing major roles in the energy arena. A best-case scenario is one where cost-effective scientific and technological solutions are found to Earth-scale systems problems but do not have serious political, social, or economic externalities.

Our vision of science and technology has matured over the last decade to where it is widely understood that no matter how much we wish this scenario to become reality, it is not likely that this scenario will unfold. It is increasingly clear that every technological solution has drawbacks and will require rational consideration of tradeoffs. For example, environmental/energy solutions such as harnessing wind and biomass raise concerns about environmental aesthetics (Johansson and Laike 2007) and food prices (Timilsina et al. 2012), respectively, and may have unanticipated environmental impacts (e.g., on bird populations or soil erosion). Intensive monitoring of Earth-scale systems and human use of and interaction with these systems may raise serious concerns about privacy. Various scenarios of technological convergence may solve energy, climatic, and other environmental problems while requiring significant changes in our conceptions of employment and the roles of markets, government, and the nonprofit world (Tonn 2012). Complicating matters further are the realizations that all Earth-scale systems are dynamically connected and our data and knowledge about the systems are limited.

The acceleration of technological change, in part fueled by advances in NBIC technologies, ironically has increased impatience in finding and implementing scientific and technological solutions. Even though at some level people must understand that changing any Earth-scale system is much more difficult than creating the next version of the iPhone, the pace of technological change witnessed by people in their lives cannot help but influence their expectations for swifter technological changes to solve Earth-scale system problems (Gleick 1999; Davis and Meyer 1998). One can argue that balancing impatience is humanity’s embracing of the concept of sustainability. Over the past ten years, there has been a sea change in thinking about the future of the Earth, from grassroots nonprofit organizations (e.g., see ICLEI Local Governments for Sustainability, http://www.iclei.org) to corporate boardrooms (e.g., the International Institute for Sustainable Development, http://www.iisd.org/), to global institutions (e.g., the United Nations Division for Sustainable Development, http://www.un.org/esa/dsd/ and the World Bank3), where the connective thread is sustainability. The sea change involves the now almost universal acceptance of the concept of (global) sustainability as a fundamental human societal value.4 This means that people and governments the world over are truly concerned about Earth-scale systems and are dedicated to finding long-term solutions, which may help to temper impatience with forthcoming solutions.

### 3.1.2 The Vision for the Next Decade

#### Knowledge Systems

One trend that can be expected to accelerate in the next ten years is the globalization of Earth-scale systems research, especially research on Earth-scale environmental systems. Research capabilities are rapidly improving in Asia, South America, and Africa, to complement those in Western countries. Global climate modeling will continue to increase in spatial resolution, facilitating more effective regional modeling and climate policymaking. New data describing natural and human

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4 Because of this, prospects for renewable energy, for example, have gone from if they will ever be widely implemented to when they will be implemented and how best they can be integrated into existing electricity grids.
systems (e.g., data describing the environmental impacts of products over the course of their life cycles) will foster the development of more powerful analytical frameworks and the integration of systems analysis across theoretical disciplines. Frameworks will be developed to more readily identify opportunities to synthesize NBIC technologies for convergence on Earth-scale system platforms to produce synergistic benefits for humanity (i.e., CKTS).

One can also imagine that the number of boundary organizations will increase tremendously, following the lead of the Intergovernmental Panel on Climate Change (IPCC) internationally and various very successful efforts in the United States and other countries. Advances in information and cognitive technologies, many noted below, will facilitate improvements in online group collaboration and access to data, models, and information. As the world’s societies continue to flatten (Friedman 2005), collaborative public policymaking will become the de facto standard approach to deal with Earth-scale systems.

**Monitoring Systems**

Monitoring of the environment, and energy, telecommunication, and infrastructure systems will increase by several orders of magnitude as the cost of sensors, cameras, tracking devices, and other equipment drops precipitously, along with the costs of transmitting and storing such data. Real-time data coverage of air and water quality and transportation systems will continue to increase. Technology will allow the closer monitoring of agricultural lands and crops, livestock, and water supplies. Ecosystem monitoring will improve through expanded satellite coverage and the tagging of key indicator species with tracking technology. Increasingly, people will wish to monitor not only their own health in real time but also their surroundings for toxic substances (Bostrom 2003).

**Communication Systems**

One can confidently assume that the capabilities of the globe’s communications systems will continue to increase. Computing speeds and telecommunication bandwidths will continue to increase (Kurzweil 2005). Mobile computing platforms will become ubiquitous and more functional. More data, information, models, resources, and applications will become available to researchers and the public. Advances in information technology and nanotechnology will underlie these achievements. However, advances in cognitive technologies, in combination with advances in intelligent software, will be needed to assist users in accessing and using these resources. Software will seamlessly cascade models, aggregate content from social networking databases, customize presentation of complex information to non-experts (e.g., to overcome common heuristics and biases; Kahneman, Slovic, and Tversky 1982), and present visualizations of complex phenomena. A new generation of sophisticated systems will be developed to facilitate R&D collaboration as well as policymaking with respect to Earth-scale environmental systems.

**Management Systems**

One can envision that over the next ten years, management of Earth-scale technological systems will become much more sophisticated. For example, to increase reliability and incorporate increasing contributions from renewable energy sources, electrical grids will become “smart.” In this same vein, intelligent transportation systems will be deployed to improve the efficiency and safety of highways and transit systems.

During this period of time, scientists and policymakers will more seriously consider options for managing the global environment, especially if early signals are confirmed that the global climate is changing more rapidly than forecast. Innovative and creative experiments will be designed to test various schemes for carbon sequestration and climate cooling. More intensive management of regional water systems, natural amenities (e.g., forests, wetlands, fisheries), and hot spots of

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biodiversity can be expected. All these improvements in management of Earth-scale systems will be supported by more robust databases created from a combination of more ubiquitous monitoring systems and pervasive global communications systems. Computer modeling and simulation of Earth systems will continue to improve as computers become ever more powerful and as more data are available to build and validate the models.

**Earth-Scale and Other Technological Systems**

One can envision substantial advances driven by NBIC technologies in the global energy sector over the next ten years. Advances in nanotechnologies will dramatically increase the efficiencies of lights and photovoltaic cells and decrease the costs of hydrogen fuel cells. More broadly, materials research will lead to advances in composites for blades for wind turbines and car bodies, among many applications that impact the energy sector (e.g., high-temperature superconducting materials or carbon nanotubes for high-voltage transmission lines). Advances in biotechnologies will benefit the production of hydrogen and other fuels (e.g., from algae) and reduce the costs of cellulosic ethanol and other energy crops. A convergence of technologies will improve the capabilities to store energy from renewable sources in batteries and other media. A convergence of information and cognitive technologies will help individuals reduce energy use in their homes and vehicles.

The immense investments needed to build and maintain the world’s infrastructure will spur an explosion of research and new technology development. Improvements will be made in systems designed to capture carbon during the production of cement. Innovations will continue in the areas of drinking water purification, road building materials, railroad technology, bridge building materials, and waste water management.

One major trend anticipated over the next decade is the globalization of space. The number of countries with space programs will continue to increase, as will their financial commitments to space programs (Devezas et al. 2012). Opportunities for international collaboration and competition will increase.

Advances in space systems will follow several lines of investigation. Commercial space activity will benefit from continued improvement in materials used to construct spacecraft on the one hand, and demands for space-based manufacturing of advanced nanomaterials and other materials on the other hand. Advanced robotics can be expected to play a major role in the latter. Nanotechnology and information technologies will converge to allow the development of more reliable and functional unmanned space exploration technologies. Nano-, bio-, information, and cognitive technologies will further converge on the problem of manned space exploration, with the design goal of allowing humans to live in space or on other planets without the need for resupply from Earth. Systems will be designed to provide power in the form of microwaves to the Earth from space and to deploy materials to shield portions of the Earth from the sun in order to cool the Earth’s atmosphere, but these will probably not be built during the next ten years.

### 3.2 ADVANCES IN THE LAST DECADE AND CURRENT STATUS

#### 3.2.2 Knowledge Systems

Knowledge systems that benefit research on Earth-scale systems are numerous, most of which have been supported by advancements in information technology. Over the past ten years, advances have been made in:

- **Complex and nonlinear systems**
- **Theoretical frameworks for understanding Earth-scale environmental problems (e.g., resiliency theory, ecological footprints)**
- **Emergence of Earth systems science as an organized discipline**
• Data mining
• Machine learning, from genetic algorithms to neural nets
• Computer visualization, from power walls to 3D modeling
• High-performance computing
• Global climate modeling
• Crowd-sourced research supported by distributed computing data analysis

There have also been advances in the overall knowledge network (Cash et al. 2003; Sarewitz and Pielke 2007; Jacobs, Garfin, and Lenart 2005). A prime example is the emergence of the Intergovernmental Panel on Climate Change as a well-respected global knowledge network that has significant influence on the management of the global environment. Boundary organizations, which are usually universities, have also arisen during the past ten years (Guston 2001; Andrews et al. 2008). These organizations are seen as neutral parties and facilitate and supply technical information to public policy decision-making processes that address Earth-scale and regional-scale environmental and energy system issues.

Within the United States there are several examples of advances in knowledge networks that could be cited, such as those that connect public-supported land grant colleges, local irrigation district managers, and county extension agents who, among other things, transform highly technical knowledge about, say, drought, climate variability, and crop and livestock conditions into information useful to farmers, ranchers, local governments, and homemakers (Cash 2001). Another example is the Regional Integrated Sciences and Assessments (RISAs) of the U.S. National Oceanic and Atmospheric Administration (NOAA), which seek to facilitate communication among various disciplines, within specific regions, regarding the possible impacts of climate change on regional resources and economies (NRC 2008). Again, the RISAs connect generators of knowledge with users such as members of the public or policy community who need this information to manage drought, alleviate flood damage, water their crops, and even manage fire hazard risks. These “networks” share another feature: they mediate between disciplines, translate science into usable forms, and integrate user needs into knowledge-generators’ activities.

3.2.3 Monitoring Systems

Many advances in Earth-scale systems research can be traced to substantial improvements in data gathering and management that support both statistical analysis and systems modeling. Real-time and longitudinal monitoring of a host of Earth-scale system indicators, many of them environmental, has improved tremendously. These indicators include:

• Air quality
• Water quality and supply
• Global air and ocean water temperatures
• Traffic and congestion
• Land use changes
• Global electric (illustrated in Figure 3.2) and magnetic circuits
• Sun–Earth interactions

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3. Convergence Platforms: Earth-Scale Systems

3.2.4 Communication Systems

The information revolution has continued unabated and maybe even accelerated over the past ten years. Moore’s law continued to hold. Bandwidth and access to computer networks continued to expand. Hundreds of millions of people worldwide now have mobile devices and access to tens of thousands of applications. Computing resources residing in the “cloud” further facilitate mobile applications and collaborative computing. Social networking has burst onto the scene. Some believe that now only there are only four degrees of separation among most of the world’s population because of the ubiquity of cell phones and social networking sites. Access to Earth-scale systems data and information has increased.

3.2.5 Management Systems and Tools

Access to more and higher-quality data more readily has contributed to the improvement of management systems. Global positioning system technology is positively contributing to the management of the transportation infrastructure and to the tracking of key aquatic and terrestrial species (e.g., Clark et al. 2006). Improvements in modeling and simulation are allowing more informative and reliable predictive management that incorporates information about location and timing of extreme weather events, potential brownouts and blackouts of electricity systems, and disruption of global telecommunication systems from solar activity.

3.2.6 Earth-Scale and Other Contributing Technological Systems

Wind and solar energy are two industries driving the creation of new jobs, pushed by significant amounts of government and corporate R&D funding for renewable energy (see Figure 3.3).
Biofuels are becoming more viable, such as in Brazil, although concerns over tradeoffs between fuel and food are still very legitimate. Advances in materials science have led to steady improvements in the energy efficiency of lights, furnaces, air conditioners, insulation, windows, hot water heaters, computers, and consumer electronics. Similar stories describe advances in the efficiency of vehicles characterized by more efficient motors and transmissions and lightweighting of materials.

During the last ten years, advancements and investments in space have been comparatively limited in Western Europe and North America, while there has been significant growth in space programs and associated technologies in the developing world, and particularly in China (which launched its first manned orbital mission in 2003 and plans a permanently manned space station by 2020), India, and Korea. There is only one major operational manned platform currently orbiting the Earth. The number of probes sent to explore other astrological bodies has been relatively few, although there have been significant successes such as the U.S. robotic explorers on Mars.

Private sector investment in space has grown significantly over the past ten years, spurred in part by the Ansari X-prize ($10 million for the first non-government organization to launch a reusable manned spacecraft into space twice within two weeks), which was awarded to the Scaled Composites Tier One team in 2004, but stimulated many other contestants and the development of a variety of novel launching and recovery technologies. Meanwhile, NASA further stimulated innovation in the private launch industry by sponsoring the Commercial Orbital Transportation Services (COTS) program beginning in 2006, which in 2012 yielded a successful resupply mission to the International Space Station (see http://www.spacex.com/). The program is now being extended to include crew as well as cargo resupply missions (see http://www.nasa.gov/offices/c3po/home/c3po_goal_objectives.html). A number of privately funded companies are planning commercial space tourism flights (e.g., Virgin Galactic, further developing the Scaled Composites technologies, http://www.virgingalactic.com/), and even mining of near-Earth-approaching asteroids (see http://planetaryresources.com). These activities have underlined the importance of the general S&T infrastructure in the United States and the importance of involving various sectors of the society in a holistic approach.

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8 See http://en.wikipedia.org/wiki/Chinese_space_program
9 http://en.wikipedia.org/wiki/Ansari_X_Prize
10 http://www.nasa.gov/offices/c3po/home/cots_project.html
3. Convergence Platforms: Earth-Scale Systems

The picture with respect to infrastructure is mixed. Previously, less developed countries such as China and India have embarked upon ambitious programs to build new roads, bridges, high-speed rail lines, dams, subways, and ports. China’s electricity production and transmission infrastructure increased in size tremendously this past decade. Conversely, infrastructure investments in the developed world have lagged behind, resulting in systems that are in dire need of repair and replacement. Figure 3.4 presents a recent alarming scorecard for the infrastructure of the United States.

Contributions of NBIC technologies to improving infrastructure materials and infrastructure management systems have been modest during this period of time. More sophisticated information systems run transportation and other infrastructure systems. Green chemistry has shown some promise to reduce the negative externalities of cement production. This limited set of achievements is not surprising because NBIC investments have generally not focused on infrastructure issues.

3.3 GOALS FOR THE NEXT DECADE

The convergence of NBIC technologies and knowledge systems could help to achieve the following types of goals related to meeting Earth-scale challenges:

- Build a knowledge platform to provide seamless access to integrated data and models supporting Earth-scale science.

- Increase access to these resources for policymakers and citizens by emphasizing translational research devoted to interpretation of NBIC technology capabilities to broader publics.

- Improve user interfaces and visualization techniques to empower researchers and others to gain unprecedented insights into environmental data and model outputs. Expand outreach and engage potential customers in the design and implementation of these new tools.

- Develop and implement real-time indicators of global environmental systems health. The concept “health” should include not just baseline conditions but also approaches to improve understanding of natural variability and causes of observed events.

- Reduce species extinction rates (or slow their rate of increase). Technological solutions include more efficient land use for food, human settlements, recreation, mineral extraction, and other resource extraction.

- Develop frameworks and tools to promote policy-oriented foresight with respect to Earth-scale systems and technological change.
• Commercialize a suite of NBIC2-related technologies to support the achievement of state-level “Renewables Portfolio Standards” or “Alternative Energy Portfolio Standards” goals and a national goal of 25 percent of electricity generated by renewable resources by 2025.\textsuperscript{11}

• Commercialize a suite of NBIC2-related technologies to significantly reduce emissions of greenhouse gasses (GHG) from production of materials for infrastructure projects (e.g., cement).

• Commercialize a suite of NBIC2-related technologies to significantly reduce the construction and operations and maintenance costs of infrastructure systems.

• Commercialize a suite of NBIC2-related technologies to implement large-scale and cost-efficient nanomaterials manufacturing processes.

• Demonstrate added value of converging technologies in the context of megacities.

• Utilized NBIC2-related technologies to achieve breakthroughs to significantly decrease the cost of space exploration.

• Identify NBIC2-related, high-value-added opportunities for space-based manufacturing.

• Develop a global risk assessment and warning system for potentially hazardous astronomical events (such as Sun activity, meteorites, etc.).

• Integrate these goals with other goals of high national and international importance, such as the UN Millennium Goals (http://www.un.org/millenniumgoals/).

3.4 INFRASTRUCTURE NEEDS

The research infrastructure needed to support the vision and goals set out above could have the following types of components:

• Cloud computing platforms to support seamless integration of and access to Earth-scale systems models and to support distributed searches for solutions to R&D problems (e.g., combinations of materials for composite applications)

• Software repositories to facilitate reuse and repurposing of modeling and other types of software commonly used by Earth-scale system researchers

• Shared user facilities for sensor fabrication and for advanced materials fabrication

• A global network to provide integrated real-time access to sensor data streams

• A repository or warehouse of nanomaterials available to NBIC researchers at low cost

• Converging technologies “skunkworks” centers (highly autonomous and focused on pioneering R&D), with associated discretion to pursue innovative projects

3.5 R&D STRATEGIES

Numerous kinds of R&D strategies can contribute to achieving the vision and goals set out above:

• Support of research to develop frameworks to understand and measure Earth-scale systems resiliency and, conversely, sources of system vulnerability.

• Support for small teams of researchers (e.g., who can use the above-mentioned user facilities).

• Support of use-inspired basic research. This includes identification of strategies that could better integrate scientific findings into decision-making, as well as identification of cultural and organizational barriers to the use of NBIC-inspired basic research.

\textsuperscript{11} According to the U.S. Energy Information Administration, absent extensions of Federal subsidies for renewable energy generation, the projected share of U.S. electricity generation coming from renewable fuels (including conventional hydropower) will be only 16 percent by 2040, although this figure is sensitive to natural gas prices and the relative costs of alternative generation; see http://www.eia.gov/forecasts/aeo/er/early_elecgen.cfm.
• Replicate the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Platform on Biodiversity and Ecosystem Services models to foster global collaboration in Earth-scale systems research.

• Continued support for innovative approaches to multidisciplinary education.

• Support projects that explicitly explore the convergence of NBIC technologies on Earth-scale system platforms (e.g., the global energy system).

• Support for research into developing frameworks for thinking about technology convergence.

• Support for research and processes to eliminate the “valley of death” that separates laboratory advances from real-world applications. This includes identifying the work contexts and circumstances of scientists and decision-makers and possible institutional impediments to innovation.

• Adopt practices to improve university and national laboratory research and industrial R&D. This should include investigation of technology transfer impediments such as patenting, licensing, and other comparable policies and rules that tend to inhibit adoption of technologies.

• Support foundational research to catalyze private-sector development of commercially viable space businesses.

3.6 CONCLUSIONS AND PRIORITIES

Meeting the challenges involved with improving Earth-scale systems requires advances in knowledge, monitoring, communications, and management systems, combined with better approaches for constructing the built environment. Presently, one can argue that ameliorating and adapting to global climate change is the top priority. This is because the risks of global climate change are potentially immense to humanity and other species that inhabit the Earth. Reducing GHG emissions through renewable energy, energy efficiency, and other technological advancements can have many additional economic benefits, for example, by increasing economic productivity and decreasing vulnerability of economies to energy price shocks. The convergence of technologies that could achieve these goals could also enhance self-sustainability and therefore could empower the achievement of human potential. Insight-producing knowledge systems built upon the foundations of ubiquitous monitoring and effective communication systems are needed as the backbone of these activities. Advances in space can contribute to monitoring and communications systems as well as to future global energy systems.

These goals and priorities are interrelated with many themes addressed in other chapters of this report. For example, global-scale efforts to improve energy, transportation, and water systems need to be integrated with local sustainability initiatives (Chapter 9). Efforts to reduce industrial waste can be combined with the additive manufacturing methods discussed in Chapter 7. The use of boundary organizations to facilitate collaborative decision-making about Earth-scale systems can be a shared goal to improve human quality of life (Chapter 2) and improve governance of NBIC technologies (Chapter 10).

It is also important to consider goals beyond the next ten years. Here are four proposed initiatives that bundle together several converging knowledge and technology aspects:

• **Global Data & Information Infrastructure** (“GDDI”). Tremendous added value would be created by seamless integration of global data across spatial scales, contexts, and time (e.g., from brains to space). Contributing to this initiative would be wearable sensing devices that individuals would wear on their wrists and that could collect a range of environmental data, transmit the data to the cloud for aggregation in real time, and then display, also in real time, key global health indicators.
• **Global Catastrophic and Existential Risk Assessment** ("GCERA"). Convergence of human knowledge is needed to understand and estimate these types of long-term risks. A convergence of data and modeling tools would be needed to support this initiative, along with theoretical advances in the estimation of existential risks and an IPCC-like organization to manage the assessment processes (e.g., see Figure 3.5, which presents a set of existential risks by source and interaction, along with a range of potential prevention and adaptation options).

![Figure 3.5](image)

**Figure 3.5** Existential risks and prevention/adaptation options (Tonn and Stiefel 2011, courtesy of B. Tonn).

• **Global Mega Cities Initiative** ("GMCI"). This initiative focuses on comprehensive systems analyses and integrated intelligent system solutions to use resources more efficiently and improve the quality of life of residents of megacities. To achieve these goals, these types of systems would need to be intelligently integrated: smart grids and systems that generate and store locally produced energy; intelligent transportation systems; systems that manage drinking and waste water systems; smart homes; and systems that may manage local, decentralized manufacturing.

• **Global Materials Initiative** ("GMI"). The organizing concept of this initiative is the transformation of megacity and/or industrial ecosystems to be composed of materials that are infinitely recyclable, reusable, and renewable ("IR3"). A convergence of knowledge and technology would need to focus on creating these materials (see Chapter 9). "Nano-tagging" of metals and components can make materials tracking, recycling, and reuse more efficient. One could also consider co-designing these eco-systems to sequester carbon in the built environment.
The following are some additional visionary convergence ideas related to Earth-scale systems:

- Improve distribution of human activity on the Earth to improve overall efficiency in using natural resources, increasing productivity, and protecting health.
- Create a global electricity grid (e.g., see http://www.geni.org/energy/assets/swf/Dymax_grid_flows.html), and develop a global system of deep geothermal facilities and a space-based microwave system to power this grid. Design and build an operational space elevator to support the latter.
- Improve the efficiency, effectiveness, and safety of transportation systems around the world through use of high-speed rail lines, driverless vehicles, and other emerging solutions.
- Develop methods and approaches to dematerialize Earth-scale infrastructures (e.g., remove dams, develop permeable highways).
- Meet a substantial fraction of the world’s demand for fresh water with energy-efficient and environmentally benign desalination technologies.
- Design and build comprehension support software that would work collaboratively with users to facilitate learning about complicated, massive “systems,” from human behavior in megacities to actions within a cancer cell or human brain, to the architecture of billion-transistor chips and multimillion-component smart grids.
- Design Web X.0 to provide real-time feedback between human activities, Earth-scale systems status, and decision-making across scales of activities and systems operations.

With respect to Earth-scale systems, one can argue that convergence can take on many forms. Here are five forms that emerged from various NBIC2 workshop discussions:

- Kurzweilian. A large number of exponentially changing technologies converge on a platform (e.g., megacities’ culture, social fabric, economics).
- Added value. Convergence components come together in a system that offers more than the sum of its parts (e.g., see the “GDDI” proposal above; global environmental systems monitoring and management).
- Synergistic. Convergence components come together to create a new, tightly integrated system where none of the components can be removed without destroying the system (e.g., IR3, user-friendly communication systems, wearable computing).
- Transdisciplinary. Disparate knowledge converges to produce new knowledge (e.g., see the “GCERA” proposal above; systems knowledge, comprehension support systems).
- Consilience. Ideas, concepts, methods, and/or tools developed in one area of science are used to help explain phenomena in other areas, creating intellectual threads tying the areas together.

Lastly, with respect to Earth-systems-focused converging knowledge and technologies R&D, these challenges must be met:

- Synthesis. Determine how best to synthesize NBIC technologies to meet Earth-systems-scale challenges to produce added value.
- Synergies. Determine how best to promote the synergistic benefits of converging technologies.
- Technological foresight. Determine how best to assess nontechnological barriers, social and environmental impacts, and unintended consequences.
- Governance. Determine how best to promote synthesis and synergies and deal with issues raised through foresight exercises.
3.7 R&D IMPACT ON SOCIETY

Protection of Earth-scale systems is essential for providing the security that, globally, all individuals will be provided with clean air and water, high-quality and reliable food, and aesthetically pleasing environments. Provided the security that essential needs will be met, humans are then free to achieve their potentials. Certainly, the construction, operation and maintenance of Earth-scale systems are a source of jobs. These systems are among the most sophisticated, extensive, and expensive that humankind has ever produced. Countries with innovative cultures and a strong base in science, technology, engineering, and mathematics will be the most competitive in designing and building these systems in the future.

3.8 EXAMPLES OF ACHIEVEMENTS AND CONVERGENCE PARADIGM SHIFTS

3.8.1 Water Management in Three World Regions: Translating Science

Contact person: David L. Feldman, University of California, Irvine

This section discusses three examples from the water sector that illustrate convergence among Earth-environmental-scale systems to achieve sustainability. They are from Brazil, Nigeria, and the Southeastern United States (Beller-Sims et al. 2008). Each one illustrates the challenges that might be addressed by converging knowledge and technology for Earth-scale systems under varying levels of national development. For each case, we consider four component subsystems: monitoring, communication, management, and cross-cutting interactions.

State of Ceará, Brazil: Climate Information and Empowered Decision-Making

In Brazil as in many rapidly developing countries, climate and weather information are collected by national- or state-level agencies and translated to various users. In 1992, in response to a long, severe drought, the water management agency COGERH of the state of Ceará (Figure 3.6) established a new system of multilevel water management for climate information. While COGERH continued to monitor weather data and communicate it to users (i.e., farmers and urban users), efforts were made to better translate information and ensure cross-cutting innovation to solve weather- and climate-related problems. Three specific reforms were pursued, as described below.

Figure 3.6 Brazil’s Ceará State (open source: http://www.ceara.gov.br).
First, COGERH simplified reservoir modeling to enhance local users’ knowledge about river basins and the risks shared by various groups as a result of drought. Local ways of conceiving of water flows were combined with sophisticated computer models.

Second, the state of Ceará enacted a new law for water management that created local watershed users’ commissions as well as a state-level Water Resources Council (Lemos and Oliveira 2004; Formiga-Johnsson and Kemper 2005; Pfaff, Broad, and Glantz 1999). The state-level council, in turn, formed an interdisciplinary group comprised of social and physical scientists and local water users to better engage stakeholders in how to use and manage climate information (Lemos and Oliveira 2005). Meanwhile, local users’ commissions negotiated water allocation among different users directly instead of relying on nationally determined allocations as had been done in the past. Both of these efforts encouraged a “bottom-up” approach to use of climate information for locally directed water allocation (Lemos and Oliveira 2004).

Third, at the river-basin level, the state water council trained users to use climate information to make more adaptive decisions in response to rainfall variability, and social science was better incorporated into decision-making to optimize use of climate forecast tools in specific management contexts. Evaluations have concluded that these reforms have helped build social capital in local communities with regard to information use and democratized decision-making, and have helped citizens better understand the different ways in which seasonal forecasting works, does not work, and could be improved (Lemos et al. 2002; Lemos 2003; Lemos and Oliveira 2004; Taddei 2005; Pfaff, Broad, and Glantz 1999). While use of seasonal climate knowledge is limited so far and many logistical problems remain (e.g., continued ignoring of local knowledge and experience in some regions, and lack of available seed distribution and other economic incentives), there is great potential for use of well-translated seasonal forecasts to improve water management in the region.

**Northern Nigeria: Adaptive Management and Local Initiative**

Since the early 2000s, Nigeria has pursued an ambitious effort to reverse environmental degradation and the loss of rural livelihoods in an 84,000 km² region in the Hadejia-Jama’are-Komadugu-Yobe river basin (Figure 3.7). Between 1970 and 1992, Nigeria’s federal government built two projects to provide irrigation and flood control: the Tiga and Challawa Gorge Dams. From the very start, the projects suffered from unexpected adverse impacts, including slow flows in the Hadejia River, high turbidity in the Challawa, large deposits of silt behind the dams leading to greater downstream floods, and infestation of Typha grass, a hard-to-remove herbaceous plant notorious for clogging streams and irrigation channels. These impacts led to losses of farmlands and grazing lands and severe losses of local fisheries, all of which revealed the need for state-of-the-art converging knowledge and technologies.

Historically, decisions regarding water monitoring, communication, and management in the Hadejia region have been shared by several federal, state, and local agencies, which has led to rival plans for river basin development and management, and fragmentation of information. Agencies’ plans were poorly coordinated: the same agencies charged with regulating water use are also large water users; thus, conflicts of interest were common. In 2002, a stakeholders’ forum in the basin was convened with the support of the International Union on Conservation of Nature (IUCN), several Nigerian ministries interested in improving agriculture and water policy, and the United Kingdom’s Department for International Development, which has an abiding interest in sustainable development (Barbier 2002).

Called the Joint Wetlands Livelihood (JWL) project, the forum instituted community-level improvements in how to use water information and introduced pilot projects to demonstrate best-management practices to restore livelihoods. A coordinating committee is brokered by high-level directors and permanent secretaries within the ministries. This committee fosters exchange of ideas between local farmers and government officials. In turn, local forums comprised of farmers, women’s groups, and others advise the JWL and provide community-level training.
Within the watershed, farm and village groups are regularly convened in a series of role-playing tabletop “games”: farmers serve as students and simulate solutions to local watershed problems by using information generated by central government climate and water data platforms. Over two days, participants engage in four distinct sessions that:

1. Allow them to brainstorm methods they think would work to maintain income and production while using less water
2. Prioritize these methods by a system of voting, so that farmers and other users agree on what works best. Their votes then become the basis for by-laws and agreements by farmers so that they can try these methods when they return home
3. Divide into two groups, one of which discusses the role of the watershed authority and the other of which discusses other formal institutions
4. Provide a final review that evaluates future actions (Lankford 2005)

Over the past decade, the JWL has mobilized local laborers to clear typha grass blocking waterways, restored some dry-lands farming and fisheries in the region, and helped build local capacity to manage freshwater problems without resort to large, highly engineered waterworks. Federal ministries support these efforts and provide technical support and translational science to communities, while villagers applaud these small-scale ventures because they participate in their implementation. Instead of grandiose public works projects, the region now increasingly relies on “gravity flow” irrigation, small dams and irrigation works, and microscale investments in the current floodplain economy (Muhammade et al. n.d.).

Southeast U.S. Climate Consortium, Regional Integrated Sciences Assessment: Building Capacity

The Southeast Climate Consortium (SECC) is an association of academic researchers from universities in Alabama, Georgia, and Florida. Like other U.S. National Oceanic and Atmospheric Administration (NOAA) Regional Integrated Sciences Assessments, the primary purpose of SECC is to develop the capacity of local stakeholders—decision-makers, farmers, ranchers, and forestry managers—to better utilize climate information for managing water-related issues. Unlike other
capacity-building approaches, however, SECC has since its formation in the 1990s relied upon top-down provision of information focused on this region’s multibillion-dollar agricultural sector (Jagtap et al. 2002). Early in its existence, SECC researchers recognized the potential to use knowledge of the impact of the El Niño Southern Oscillation on local climate to provide guidance to farmers, ranchers, and forestry sector stakeholders on yields and changes to risk (e.g., frost, floods, drought). Through a series of needs and vulnerability assessments, SECC researchers determined that the potential for producers to benefit from seasonal forecasts depends on factors that include their flexibility and willingness to adapt farming operations to the forecast, and the effectiveness of the communication process, and not merely on documenting the effects of climate variability and providing better forecasts (Jones et al. 2000; Hildebrand et al. 1999).

Extension specialists and faculty are members of the SECC research team. SECC engages agricultural stakeholders through communication and outreach efforts, including video conferences, one-on-one meetings with extension agents and producers, training workshops designed to instill confidence in climate decision tool use and to identify opportunities for their application, and traditional extension activities such as commodity meetings and field days (Fraisse et al. 2005). SECC is also able to draw upon the trust that the cooperative extension’s service to the agricultural community has built up in the region through its various online tools such as AgClimate (e.g., Fraisse et al. 2006). Direct engagement with stakeholders has provided feedback to improve the design of these tools and to enhance climate forecast communication (Breuer et al. 2007).

Current activities of SECC are focused upon improving understanding of seasonal climate variability and climate predictability at local to regional scales across the South; characterizing contributions of climate variability to risks in management of agricultural, forestry, and water resources; developing decision aids based on the use of climate forecasts to help decision-makers identify management options to reduce risk; design and implement appropriate vehicles for disseminating climate and decision support information (e.g., an Internet-based learning and decision support system); and develop partnerships to build socially equitable extension and outreach programs (Southeast Climate Consortium, http://www.seclimate.org/objectives.php).

In conclusion, SECC appears to have been successful in integrating new information with established interaction networks (i.e., agricultural producers and extension agents). Its own evaluations suggest that benefits from producers’ use of seasonal forecasts depends on several factors: the flexibility and willingness to adapt farming operations in response to forecasts; the effectiveness of forecast communication; sustained interactions with agricultural producers in collaboration with extension agents; and direct engagement with stakeholders that provides feedback on how to improve climate forecast communication.

3.8.2 Unifying Earth Databases: Data Observation Network for Earth (or Spaceship Earth Mission Control Center)

**Contact person:** Alexander MacDonald, NASA

A convergence initiative is necessary for planetary sustainability. NASA has proposed the Spaceship Earth Mission Control Center (SEMCON) in order to create an immersive data visualization environment for collaborative interdisciplinary research, modeling, and education focused on understanding the entire Earth system environment, the dynamic human impact on it, and decision options for effecting long-term planetary sustainability. Experts from a wide variety of scientific and research disciplines will be involved for good understanding of options for long-term planetary sustainability and economic development, including climate scientists, oceanographers, modelers, energy experts, nanotechnologists, systems biologists, information scientists, data visualization experts, economists, cognitive scientists, behavioral sociologists, political scientists, policy analysts, and others. The initiative is intended to become a kind of Manhattan Project for planetary sustainability, suited to a public–private partnership.
3.8.3 Global Nano-Geobiochemistry

Contact person: Michael F. Hochella, Jr., Virginia Polytechnic Institute and State University

Global nano-geobiology is a relatively new NBIC field of study that is becoming somewhat established even though it has only appeared in the last few years. It is a classic example of a convergent platform of an Earth-scale system, only made possible due to knowledge, monitoring, communication, and management system components, as defined earlier in this chapter, that have been developing and maturing for decades. With each of these systems now reaching a critical level of maturity in support of understanding Earth’s nanochemistry, geochemistry, and biochemistry, convergence allows for global nano-geobiology to efficiently develop and provides opportunities for broad, global-scale thinking that was not possible just a few years ago. Below, we provide two examples of the power of a global nano-geobiology convergent platform based on the NBIC model. These examples, both dealing with long-term Earth sustainability, show that broad implications and predictions in complex systems can be achieved.

Iron Fertilization of the Oceans

Here is an example that most strongly captures the essence of global nano-geobiology (Hochella et al. 2008 and 2012, and many references therein) in a complex, profound, and very serious high-stakes scenario in which the human race is deeply engaged. Over the last century, Earth mean surface temperature has increased by 0.8 degrees Celsius, and the rate of temperature increase is likely accelerating. This warming is a direct observable, and is therefore indisputable. A general consensus of the world’s climate science academic communities puts the probability of this increase stemming from human-induced global climate change at about 90%, via the massive and still rapidly accelerating burning of carbon-based fossil fuels, as well as deforestation. Global warming is most often named by Earth scientists as by far and away the most important environmental issue of our times, and the number one Earth sustainability issue literally for centuries to come.

Global nano-geobiology is central to this unfortunate situation, as global temperatures to a significant degree involve phytoplankton production levels in the open oceans, a process that provides a connection between nanoparticles, oceans, and global atmospheric and hydrospheric chemistry. The foundational scientific discussion that directly follows here, describing this situation, leads to possible actions that have at least some potential for ameliorating what could otherwise be a global, long-term, very difficult or dire situation. This possible action to consider is iron fertilization of the oceans.

Phytoplankton, as highly abundant chlorophyll-containing autotrophs populating the sunlit portions of nearly all oceans and continental surface waters, accounts for about half of the photosynthetic activity on Earth and are therefore one of Earth’s single most abundant consumers of atmospheric CO₂. We also know that ocean phytoplankton populations are often nutrient-limited, primarily due to limited iron availability. This is where nanoparticles come in, because potential input of iron (Fe) within nanoparticles to the oceans has been predicted to be capable of far exceeding the natural inputs of dissolved iron from rivers. This is due to the fact that ferric (oxidized) iron, which is by far the dominant iron species in the Earth surface’s highly oxidizing environment, is exceptionally insoluble in water.

Recently, NBIC platform development has allowed us to begin to estimate the global production of naturally occurring nanomaterials and their global movement, which is critical to understanding the supply of iron-containing nanoparticles to the world’s oceans (Figure 3.8). Although the primary production of iron-containing nanoparticles in the oceans is far from being quantified due to lack of sufficient information about such a massive and remote system, we can say that continental soils are otherwise the most prolific producers of inorganic nanoparticles on Earth, generating an existing reservoir of \(10^{7.8}\) Tg (teragrams, equal to one million metric tons).
Clays are by far the most abundant naturally occurring inorganic nanomaterial in soils, many of which have significant Fe concentrations, but iron oxides and other iron-containing nanoscale minerals are also present. Rivers, and to a lesser extent, glaciers bring between 0.1% and 0.01% of this nanomaterial reservoir to the continental edges on an annual basis, but only about 1.5% of this makes it past continental margins and shelves to the deep oceans, due to aggregation and settling as a result of the very high ionic strength of seawater, which limits the repulsive forms that would normally prevent the particles from agglomerating. However, together with the airborne nanomaterial input via atmospheric mineral dust generated from windblown, arid, and devegetated lands (and this input rivals that from rivers), as well as much smaller but very important inputs from melting glaciers, ice sheets, and/or icebergs and hydrothermal inputs on ocean floors typically at tectonic spreading centers, the world’s oceans receive a vital supply of iron-containing reactive/catalytic nanomaterial.

These minute mineral grains are bioavailable to marine phytoplankton via a number of mechanisms, including reductive dissolution processes, direct ingestion, and probably other mechanisms. It has even been shown recently for the first time that, at least for dissimilatory iron-reducing bacteria, the rate of ferrous iron release from ferric nanoparticles is dependent on the size, shape, and aggregation state of the nanoparticles (Bose et al. 2009), very typical of nanoscale behavior observed in laboratories as well as in nature.

Being aware of and understanding this background is essential to considering, let alone attempting, iron fertilization of the oceans on a large scale. The idea is to increase the biological population and therefore productivity of phytoplankton in the oceans to take up more CO₂, presumably with
practical and logistical advantages over increasing land-based green plants that could accomplish the same thing. The idea has been around for well over two decades. Over that time, international teams of scientists have completed more than ten trials in the open oceans, often in the Southern Ocean that encircles Antarctica where the waters are relatively nutrient-rich except for iron. Many more experiments have taken place in laboratories. These ocean trials and experiments demonstrate that phytoplankton blooms can be stimulated by the addition of small amounts of iron compounds, typically submicron grains of iron sulfate. CO$_2$ consumption is increased, resulting in more biomass through photosynthesis, which is then deposited in the deep ocean as the organisms die. The chemical leverage is tremendous: each atom of iron results in the capture of roughly 13,000 atoms of carbon, due to the fact that iron is a micronutrient, but obviously still essential for growth.

However, using what amounts to geoengineering of the oceans is exceptionally controversial, ultimately and primarily based on the cognition portions of the NBIC platform. Specifically, the skill and art of taking on a highly complex situation comes into play, trying to solve problems without making new ones, and in the end, hopefully making the correct overall decision for the long term. Higher-level cognitive analysis of these types of situations suggests that when a vast, complex system is intentionally perturbed for desired benefits, unintended consequences and deficits are invariably created. This kind of scenario has been seen over and over again in attempted human engineering of the Earth’s physical and ecological environments. Ocean and laboratory fertilization tests have already revealed a potentially very serious problem. It has been seen that iron stimulation can change the balance of phytoplanktonic species populations. Even worse, if any of the organisms most favorably promoted are not wanted in higher percentages within larger populations, there is a very serious problem. This is the case with a phytoplanktonic organism like *Pseudo-nitzschia*. This organism produces domoic acid, a potent neurotoxin. As consumers take in *Pseudo-nitzschia*, domoic acid invariably moves up the food chain. This neurotoxin is known to harm fish, birds, sea mammals, as well as humans who eat contaminated seafood.

In such a grand scheme, there will invariably be unintended consequences, as well as potentially great benefits. Nevertheless, at least assessment of the ocean iron fertilization scheme has been vetted at a high level thanks to an informed NBIC platform assessment, with this in turn greatly informed by our knowledge of global nano-geobiocchemistry. Decisions in the future will continue to depend on updated knowledge, monitoring, communication, and management system components as described earlier in this chapter. Only one certainty regarding this situation is that whatever the action or inaction is in the future, we will be playing an exceptionally high-stakes game.

**Environmental Implications of Nanotechnology**

Critical areas of our understanding and preservation of Earth deal with our leading industries and their impact on the planet. One need look no further than the relationship between the energy industry based on fossil fuels, by far our greatest source of energy, and global climate change, as described earlier. When it comes to another massive and exceptionally rapidly growing industry, nanotechnology, we are much farther from understanding short- and long-term global implications, but due to NBIC convergent techniques, we are definitely on our way to a level of understanding that is already providing us with critical guideposts (e.g., Wiesner et al. 2009 and 2011 and references therein). We have started by gaining some understanding of the mobility, transformations, and ultimate fate of nanomaterials in highly complex, natural, environmental contexts. We know that we need at least this before we have any chance of developing intelligent regulation. Certainly, as nanotechnology quickly ascends industrial growth projections, and it is already well on its way to a multi-trillion-dollar industry, it is very clear that the number, chemical and structural variation, and quantities of manufactured nanomaterials will grow exponentially. Therefore, it is inevitable that Earth’s collection of ecosystems, and organisms within those ecosystems, will be exposed to various manufactured nanomaterials that will likely have transformed along their passage through the Earth system with which they have been in contact.
Yet, most interestingly, as these manufactured nanomaterials enter Earth’s natural and man-made environments, they will be, and are, in the severe minority. Naturally occurring nanomaterials are continuously forming within and distributed throughout the Earth system, in soils, surface and ground water on the continents, the oceans (as discussed in more detail in the above section on iron fertilization of the oceans), in the atmosphere, as well as directly and indirectly by biological agents, most importantly by microorganisms (nanomaterials are both organic and inorganic, the latter including metals, metal oxides, and even metal sulfides). Our estimates of the production of naturally occurring nanomaterials in all Earth compartments vastly exceeds the amounts of manufactured nanomaterials produced today, and most likely into the foreseeable future (Figure 3.9; Auffan et al. 2009; Hochella et al. 2012). The variation of the composition, atomic structure, and size/shape of both naturally occurring and manufactured nanomaterials is staggering, but there is significant overlap between these two groups, e.g., various metals, metal oxides and sulfides, and carbon-based nanomaterials.

Figure 3.9 A comparison between the annual production of inorganic nanomaterials by industry and nature (figure courtesy of Michael Hochella).

Besides engineered and naturally occurring nanomaterials, there is a third class to consider, that of incidental nanomaterials. These nanomaterials are formed, either directly or indirectly, as a result of human activity, but unintentionally. Examples include nanocarbonaceous soot from diesel engines, metals sulfides from the waste streams associated with mining activity, and nanosilver in wastewater treatment plants.

The distinction between naturally occurring, engineered, and incidental nanoparticles in the environment will always be confounded by natural and variable modification of all materials in complex environments, including of course, nanomaterials (see below), but also because there is considerable overlap between these three classes of materials. On the other hand, many of these nanomaterials will have tell-tale signs of their origin, whether characterized by direct or circumstantial evidence based on chemistry, distribution, or specific location. It is also interesting to note that the European Commission on Nanomaterials, in October 2011, provided the following definition of a nanomaterial as “a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number/size distribution, one or more external dimensions is in the size range 1nm–100 nm” (http://ec.europa.eu/nanotechnology/policies_en.html).

All nanoparticles, regardless of their origin, will transform in the environment as a result of growth or dissolution, chemical exchange, aggregation or agglomeration, recrystallization, biologic interactions, light exposure, redox reactions, and so on. Nanoparticles, depending on their type and
the geo-environment in which they find themselves, may persist for long periods of time, transform rapidly, or anything in between. At each stage, their interaction with and potential toxicity to all things biologic will vary over time relative to each species encountered.

With so much dynamic complexity, one might conclude, prematurely, that we have not made progress in our recent quest for understanding the environmental impact of nanotechnology. Nothing could be further from the truth. In the last decade, we have made dramatic gains in our understanding of nanoparticle formation, transformation, and distribution in natural and man-made environments. No doubt countless details will be filled in over the next several decades.

Due to transformative thinking resulting from NBIC platforms assembled from advanced Earth-system knowledge, monitoring, communication, and management components, we can draw useful assessments, even at this point:

1. Early Earth, although geochemically primitive relative to today, would have been well suited for producing a vast array of nanomaterials. Therefore, first life on Earth, and all evolution since, has occurred in the presence of a ubiquitous array of naturally occurring nanomaterials.

2. Very recently, humans have added vanishingly small to significant amounts of incidental and manufactured nanomaterials to the Earth system, on local, regional, and global scales.

3. Direct and indirect introduction of nanomaterials due to human activity will result in the potential of transformations and transport into and between various Earth compartments (soil, water, and organisms, including potential trophic transfer, atmosphere, and oceans).

4. The behavior of certain states of each type of nanoparticle, with respect to certain organism types, in the right environment, will result in neutral, beneficial, and toxic effects.

We now have the tools and basic understanding, which was not available until recently, to begin to monitor and study such effects. This will likely allow us to take regulation and policy actions earlier rather than later, which has most often not been the case in the past with the rapid growth of new industries and technology revolutions. Such is the benefit of NBIC platforms.

3.8.4 Impact of Convergence on NASA’s Earth Science Missions

Contact person: Michael A. Meador, NASA Glenn Research Center

The Earth is a complex, ever-changing planet. A more complete understanding of how the Earth is changing, the internal and external factors that are driving and influencing this change, and how changes in climate and the environment, and the availability and distribution of resources, impact the Earth’s ability to sustain life are critical questions that must be addressed for the future of life on the planet. In 2007, the National Research Council completed the first ever decadal survey identifying future needs and opportunities in space-based Earth Science. In its report the NRC panel states, “Understanding the complex, changing planet on which we live, how it supports life and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important challenges for society as it seeks to achieve prosperity, health, and sustainability” (NRC 2007, 19). Addressing this critical challenge will require significant developments in nanotechnology and biotechnology, information science, and cognitive and behavioral sciences in an integrated approach that draws upon the convergence of these technologies.
Advances in sensors and instrumentation, through the use of nanoscale materials and novel device architectures and fabrication techniques, are needed to enhance the accuracy and expand the capability of Earth-observing satellites (NRC 2012). Development of long-life, high-power, multibeam, and multiwavelength (0.3 to 2 \( \mu \)m) lasers (both continuous-wave and pulsed) will enable more accurate detection of atmospheric CO\(_2\) and other gases, measurement of aerosol and cloud properties and composition, and Doppler velocimetry-based wind measurement. Advances in optical detectors and hyperspectral imaging (from visible to short-wavelength infrared) will lead to improved global resource mapping and measurement of ocean activity, including 3D profiles. For example, significant enhancements have been achieved in the spatial resolution of LIDAR (light detection and ranging) through use of quantum-entanglement-based detection schemes (Dowling 2009). While quantum LIDAR has been developed for terrestrial ranging and imaging applications, it could be applied to Earth-observing satellites, such as NASA’s Orbiting Carbon Observatory-2 (Figure 3.10, above) and Earth Observatory, which recorded the image shown in Figure 3.11.

![Figure 3.11](image.jpg)

**Figure 3.11** Nighttime image of Australia captured by the NASA-NOAA Suomi NPP (National Polar-orbiting Partnership) satellite. Bright spots are sources of light from the surface, including city lighting, wildfires, and lighting on oil drilling platforms. (Photo credit: NASA Earth Observatory/NOAA NGDC, © NASA, http://www.nasa.gov/mission_pages/NPP/news/aus-fires.html, used under open-source policy.)

Improvements in the design of instrument electronics, through the use of nanoelectronic materials and devices, are needed in order to minimize power, mass, and volume requirements and enable increased instrumentation in space-based Earth observation systems. Recent developments, such as the use of self-assembly to develop high-density carbon nanotube transistors, reported by IBM scientists (Park et al. 2012), and carbon-nanotube-based nonvolatile memory, developed by Nantero, suggest possible approaches to meeting this need.

The current Earth observation system of satellites and ground-based sensors generates over 4 terabytes of information per day (NASA 2010, 31). This is expected to grow significantly as new satellites are added. The ability to process this data into useful information is critical for the development of accurate and timely representations of the state of the Earth and its inhabitants, as well as for robust models to predict changes in climate and the ecology and natural resource distribution. This will require not only radical advancements in computational hardware, including alternatives to CMOS technology, but also the development of new software architectures, e.g., cognitive and hybrid computing, that can efficiently mine and process large data sets. Some of these needs could be met by adapting technologies and approaches developed under the Human Genome Initiative, which also faced challenges with processing of large amounts of data, as well as those currently under development in the Big Data Research and Development Initiative.
Solving these problems will also enable the development of autonomous satellites with decision-making capabilities to alter their mission, based upon observed events on Earth, such as forest fires or volcanic eruptions, to collect data on those specific events. These autonomous satellites could be used in the construction of a sensor web, a distributed global network of small sensor satellites that could be used for more in-depth mapping of resources, monitoring changes in climate and geology, and monitoring disasters.

### 3.8.5 Global Climate Change Coordination in the United States

**Contact Person:** Geoffrey Holdridge, World Technology Evaluation Center

For several decades there has been a concerted international interdisciplinary research effort to document, understand, and suggest remedial approaches to global climate change. The U.S. Government’s part of this effort is coordinated through the U.S. Global Change Research Program (USGCRP, [http://www.globalchange.gov/](http://www.globalchange.gov/)) and through the Subcommittee on Global Change Research of the National Science and Technology Council. USGCRP periodically issues a comprehensive report summarizing the science of climate change and the impacts of climate change on the United States, now and in the future. It integrates the results of the U.S. program with related research from around the world and discusses climate-related impacts for various societal and environmental sectors and regions across the nation.

The 2009 USGCRP report, *Global Climate Change Impacts in the United States*, analyzes climate change impacts by sector, including water resources, energy supply and use, transportation, agriculture, ecosystems, human health, and society, and reviews ongoing and proposed efforts to remediate any adverse impacts of global climate change in each of those sectors. It also proposes an agenda for climate impacts science that includes recommendations to (1) expand our understanding of climate change impacts (including research on ecosystems and on economic systems, human health, and the built environment); (2) refine our ability to project climate change, including extreme events, at local scales; (3) expand our capacity to provide decision-makers and the public with relevant information on climate change and its impacts; (4) improve our understanding of thresholds likely to lead to abrupt changes in climate or ecosystems; (5) improve our understanding of the most effective ways to reduce the rate and magnitude of climate change, as well as unintended consequences of such activities; and (6) enhance our understanding of how society can adapt to climate change. In January 2013 an updated National Climate Assessment (NCA) report was posted as a draft for public comment (see [http://ncadac.globalchange.gov/](http://ncadac.globalchange.gov/)).

### 3.8.6 Spaceship Earth Mission Control Center: A Convergence Initiative for Planetary Sustainability

**Contact person:** Alexander MacDonald, NASA

If we are all passengers on “Spaceship Earth”, then we should consider the potential need for a sort of “Spaceship Earth Mission Control Center”—a scientific facility that could serve as a focal point for the coordinated collection of global-scale earth science and socio-economic information and for the assessment of our options for ensuring long-term planetary sustainability. We have established physical data-immersive architectures to help our leaders come up to speed on our most difficult technical challenges—from the National Military Command Center in the Pentagon, to NASA’s Mission Control Center. These are places where our national decision-makers can focus and immerse themselves in the state of affairs of national defense or spacecraft operations. But where does a newly elected President, or other world-leader, visit in order to understand the current state of affairs with regard to planetary sustainability? The construction of such a facility would be an important driver of technological convergence and would be a powerful symbol of our commitment to address the challenge of planetary sustainability today and to serve as the Earth’s caretakers on behalf of future generation.
Although the term “Spaceship Earth mission control center” implies a governance role, the concept as envisioned would have no operational environmental or industrial policy responsibilities. Instead, the emphasis would be on multidisciplinary science—on data collection, data visualization, and systems modeling within a co-located research environment inspired by NASA’s Mission Control Center in Houston. Whereas the Mission Control Center in Houston tracks the health and status of the technological subsystems of NASA’s spacecraft—e.g., power, propulsion, thermal, communications, and attitude control—the Spaceship Earth Mission Control Center would track the health and status of the Earth’s ecological subsystems—e.g., water, air, soil, flora, fauna, human action. Integrating these planetary subsystems within an overall model would require the participation of world-class experts not only from the established fields of earth and human sciences (physics, chemistry, biology, geology, oceanography, economics, sociology, psychology) but from researchers working within the emerging fields of technology that present both potential risks and solutions for sustainability—nanotechnology, biotechnology, information technology, and cognitive technologies. Although full convergence within the proposed framework would be a matter of decades rather than years, the convergence of information technologies and cognitive technologies for improved decision-making could show practical results within the decade.

The successful realization of a Spaceship Earth Mission Control Center would depend primarily on integrating the current state of the art in information technologies and stimulating new convergence technologies through the creation of unified Earth databases and an integrated data observation network for Earth. The convergence of these information technologies with the cognitive sciences of decision-making could potentially create a new practical capability for long-run planetary planning. This would in turn motivate the further development, over the coming decades, of new information collection capabilities critical to gathering planetary-scale environmental data at high resolution, including everything from low-cost remote sensing satellite constellations to integrated cellular-scale biosensor networks. In order to rise to the technological and environmental challenges of the 21st century, let alone the challenges of the 22nd century and beyond, the multidisciplinary approach embodied by converging technologies is going to be vital to providing effective situational awareness and modeling capabilities for planetary sustainability.

3.9 INTERNATIONAL PERSPECTIVES

The following are summaries relevant to this chapter of discussions at the international regional WTEC NBIC2 workshops held in Leuven, Belgium, September 20–21, 2012; in Seoul, Korea, October 15–16, 2012; and in Beijing, China, October 18–19, 2012. Further details of those workshops are provided in Appendix A.

3.9.1 United States–European Union NBIC2 Workshop (Leuven, Belgium)

This section is a distillation of several separate breakout session discussions in Leuven that pertained to Earth-scale systems, based on plenary presentations and discussions and breakout session notes. There was no single session or group that addressed this topic. Please see Appendix B for names of all attendees at the Leuven NBIC2 workshop. The sessions taken together were extremely informative in terms of conveying European perspectives, particularly the European commitment to considering the social and environmental implications of converging technologies.

Formally titled “EU–U.S. Workshop on Converging Nano-Bio-Info-Cognitive Science and Technology (S&T) for Responsible Innovation and Society,” this workshop addressed a wide range of topics related to research, governance, and innovation. The breakout group charged with discussing NBIC2 concepts and directions within the rubric of sustainability focused a good deal of attention on megacities as a platform for technology convergence. Megacities offer a rich array of challenges and opportunities for converging technology solutions. For example, with respect to transport, advanced information technologies can foster more intelligent management of traffic and mass transit systems, and nanotechnologies can lead to the lightweighting of vehicles. A
A combination of nano-, bio-, and info technologies can lead to substantial improvements in energy efficiency (e.g., for heating and lighting systems in buildings) and increases in the production of renewable energy in megacities (e.g., rooftop photovoltaics, wind, and biofuels). Nanotechnology and information technologies will underpin advancements in smart grids and energy storage.

NBIC2 technologies also promise reduction and reuse of waste in megacities. New materials could be designed to be infinitely repurposed. Intelligent decentralized manufacturing (e.g., 3D printing) has the potential to greatly reduce waste in the production process. New material separation technologies based on advances in nanotechnology could lead to the cost-effective mining of urban waste depositories. The NBIC2 workgroup participants anticipate that megacities around the world will pursue large-scale, integrated infrastructure systems solutions in order to create urban environments more attractive to high-end companies and workers and to compete globally for jobs.

3.9.2 United States–Korea–Japan NBIC2 Workshop (Seoul, Korea)

Panel members/discussants:

Hee Chan Cho (Co-Moderator), Seoul National University (Korea)
Bruce Tonn (Co-Moderator), University of Tennessee (U.S.)

Others:

Jiwan Ahn, Korean Institute of Geoscience and Mineral Resources (KIGAM, Korea)
Masafumi Ata, National Institute of Advanced Industrial Science and Technology (AIST, Japan)
Mamadou Diallo, Caltech (U.S.) and Korea Advanced Institute of Science and Technology (KAIST)
Choon Han, Kwangwoon University (Korea)
Wanseok Kim, Electronics and Telecommunications Research Institute (ETRI, Korea)
Takashi Kohyame, Hokkaido University (Japan)
Kazuto Matsubae, Tokyo University (Japan)
Shinya Nakamoto, Japan Science and Technology Agency (JST, Japan)

Due to the composition of the participants in this breakout group, technical discussions focused mainly on materials issues. Ideas that were discussed include the following:

- Improvements in desalinization techniques
- Urban mining for valuable metals
- Improvements in oil field imaging techniques
- Materials with increased surface areas good for filtration applications
- Improvements in extraction of metals from ores
- New materials to lightweight automobiles
- Scrubbing CO₂ from stacks at cement plants
- Tracking global material flows through the use of nano-tags on metals and components

The group also took the opportunity to discuss a range of associated policy and social science issues, including:

- Trust must developed by the public in scientists to recommend acceptable solutions.
- Trust must also be given to politicians to decide on best solutions for societies.
- Social systems need to be developed to foster recycling and waste reduction.

Lastly, the group identified these important education and professional issues:

- Kids in Japan, Korea, and the United States are becoming much less interested in S&T.
• Young women in these countries need encouragement to pursue S&T education and need more professional opportunities in these areas.

• In Japan & Korea, S&T careers of young women are often derailed because of marriage and children; could government policies help reintegrate women into the workplace, especially to work in converging technology areas?

• Can graduate education be designed to train students to work in the converging technology area?

• There is so much to learn; schools need to train specialists just as matter of course; however, maybe S&T generalists can be trained to manage converging technology research.

• More experiments are needed in designing programs and even universities that revolve around the solution of grand challenges (e.g., water, energy).

• Students are pushing for sustainability; if professors do not follow, they become dinosaurs.

• Maybe the solution is to find a balance where a few students can be trained to manage cross-disciplinary converging technologies research; specialists then need an open attitude to collaborate with others.

3.9.3 United States–China–Australia–India NBIC2 Workshop (Beijing, China)

Panel members/discussants:

Xingyu Jian (co-moderator), National Center for Nanoscience & Technology (China)
Bruce Tonn (co-moderator), University of Tennessee (U.S.)

Others:

Mamadou Diallo, Caltech (U.S.) and Korea Advanced Institute of Science and Technology
Craig Johnson (Australia)
Ian Lowe, Griffith University (Australia)
Lianmao Peng, Peking University (China)

The breakout group discussions related to Earth-scale systems were productive and wide-ranging. The results of these discussions are presented below. To begin, the group identified three major changes in vision over the past ten-years:

• There is now a strong realization that climate change is major threat to food production, among many threats, and is also a major health threat.

• There is acknowledgement that sustainability is now an important driver behind Earth-scale environmental system decision-making, but more needs to be done to act on this trend.

• It is now generally accepted that there are various difficult and complex tradeoffs between societal and cultural challenges versus direct technological solutions to the problems.

With respect to knowledge systems, the group offered these thoughts:

• There is a need for tools to better understand contributions of multiple factors to climate change (e.g., biological contributors).

• Researchers should not ignore behavioral change in lieu of only technological solutions. Therefore, there is a need to study system solutions—those that combine behavioral change and technological solutions—where all tools are considered that can be used to influence behavior, including education and financial incentives.

• There is a need for more effective data and analytical tool sharing among researchers, agencies, companies, etc.
• A robust computational system needs to be developed to understand upscale and downscale phenomena (e.g., global-regional-subregional climate projections).

• Australia has coral reefs and tropical rainforests; focus on these resources as key indicators of climate change. Expand this approach internationally.

• There is a need to greatly increase understanding of global environmental systems as complex nonlinear systems with dramatic phase-change thresholds.

• There is a need for more modeling and computational capabilities, resources, access, and generic modeling platforms (such as already programmed in physics, some other phenomena).

• There is a need for more cross-disciplinary, physically collocated research infrastructure.

• There is a need to leverage national R&D priorities to aggregate up to rigorous creation of knowledge for humanity.

With respect to monitoring systems, the group offered these thoughts:

• More concrete data are needed, (e.g., through a hundreds of times more dense global system of sensors) to reveal, for example, patterns of volatile organic compounds (VOCs, e.g., organic aerosols) with respect to climate change.

• Therefore, there is a need for low-cost (nanowires, nanoparticles) sensors and complex models to fuse the sensor data to feed into global climate models.

• A challenge is the low concentration of some types of particles in the atmosphere, which poses a good application for nanotechnology.

• Track key marker viruses in species to better understand species vulnerability with respect to climate change. Could climate change lead to accelerated virus mutations? If so, virus tracking could be an early warning system.

• Improve space-based monitoring of epidemiological trends, conditions, and disease outbreaks.

• Improve data/sensor coverage in the Southern Hemisphere.

• More integrated environmental observatories are needed.

The group offered these thoughts with respect to communication systems:

• Link aggregated sensor data and real-time feedback to people via their cell phones with regard to climate change. This is an example of crowd-sourced data collection and communication. Maybe even give real-time feedback on the sustainability or lack thereof of personal behaviors.

• Support improvements in video conferencing to substitute for travel.

Management systems and tools also received some attention:

• Reduce traffic congestion through accelerated implementation of intelligent transportation systems.

• Accelerate research and implementation of nanocomposites to lightweight vehicles and trains to decrease pollution.

• Change the transport task: challenge all assumptions, substitute information technology for transport, reconceptualize urban design.

• Support the rigorous and inclusive development of technology roadmaps.

These thoughts were offered concerning Earth-scale and other contributing technological systems:

• In China, major advancements in various areas of infrastructure have been made (e.g., roads, healthcare), but gaps still exist.
• Artificial photosynthesis energy storage via chemical approaches needs more attention.
• Plans should move ahead to design and build an operational space elevator.
• Create a net-zero carbon emissions cycle for transportation to help ameliorate climate change. Focus on biofuels to substantially substitute for fossil fuels.
• Use CO₂ wastes to make carbon nanotubes for storing carbon in the built environment.

At times, the discussants made points that overlap with other chapters in this volume:
• Deal with aging populations using innovative technologies and management techniques. (Chapter 5)
• Develop simple diagnostic treatment technologies that can be deployed in rural/small clinics in China and other similar contexts. (Chapter 5)
• Even in the developing world, technology seems to make people busier, but not necessarily in a good way. This trend should be reversed. (Chapter 5)
• Design better products made from wood. Use genomic information from wood to make wood inherently stronger. Then maybe one could go back to using wood for wind turbines and airplane wings, for example. (Chapter 9)
• Develop more imaginative ways of producing healthier food that are resilient to climate change and water shortages. (Chapter 9)
• Social engagement with regard to NBIC2 technologies needs to be greatly enhanced. (Chapter 10)
• Rational governance works with regard to technology development but needs to be faster. One should consider using feedback from governance processes to guide NBIC2 technology development. When targets are set by governments, technology can evolve to meet the targets. (Chapter 10)
• More efficient innovation from NBIC2 academic discoveries and advances needs to be facilitated. (Chapter 10)
• Improvements are needed in evaluating NBIC2 technology impacts on society. (Chapter 10)
• Improvements are needed in global governance and decision-making in setting global goals, processes, collaborations, and application of NBIC2 to deal with Earth-scale environmental issues. (Chapter 10)
• Design international collaborations and contributions with respect to Earth-scale systems according to capacities and needs and local/regional benefits. (Chapter 10)

The group offered these three as the top-priority issues associated with Earth-scale systems:
• Major improvements are needed in modeling of complex Earth-scale environmental systems/processes (e.g., climate change).
• Knowledge generation can be greatly accelerated through the worldwide sharing of and seamless access to important Earth-scale system R&D data, tools, and models. Responsibilities to achieve this goal need to be shared, internationally, maybe through replicating the IPCC model for various Earth-scale systems and processes (e.g., biodiversity).
• There is a need to develop more powerful and sophisticated intelligent systems to more effectively manage Earth-scale systems and communicate with all global citizens in real time about the status of the Earth.
3.10 REFERENCES


