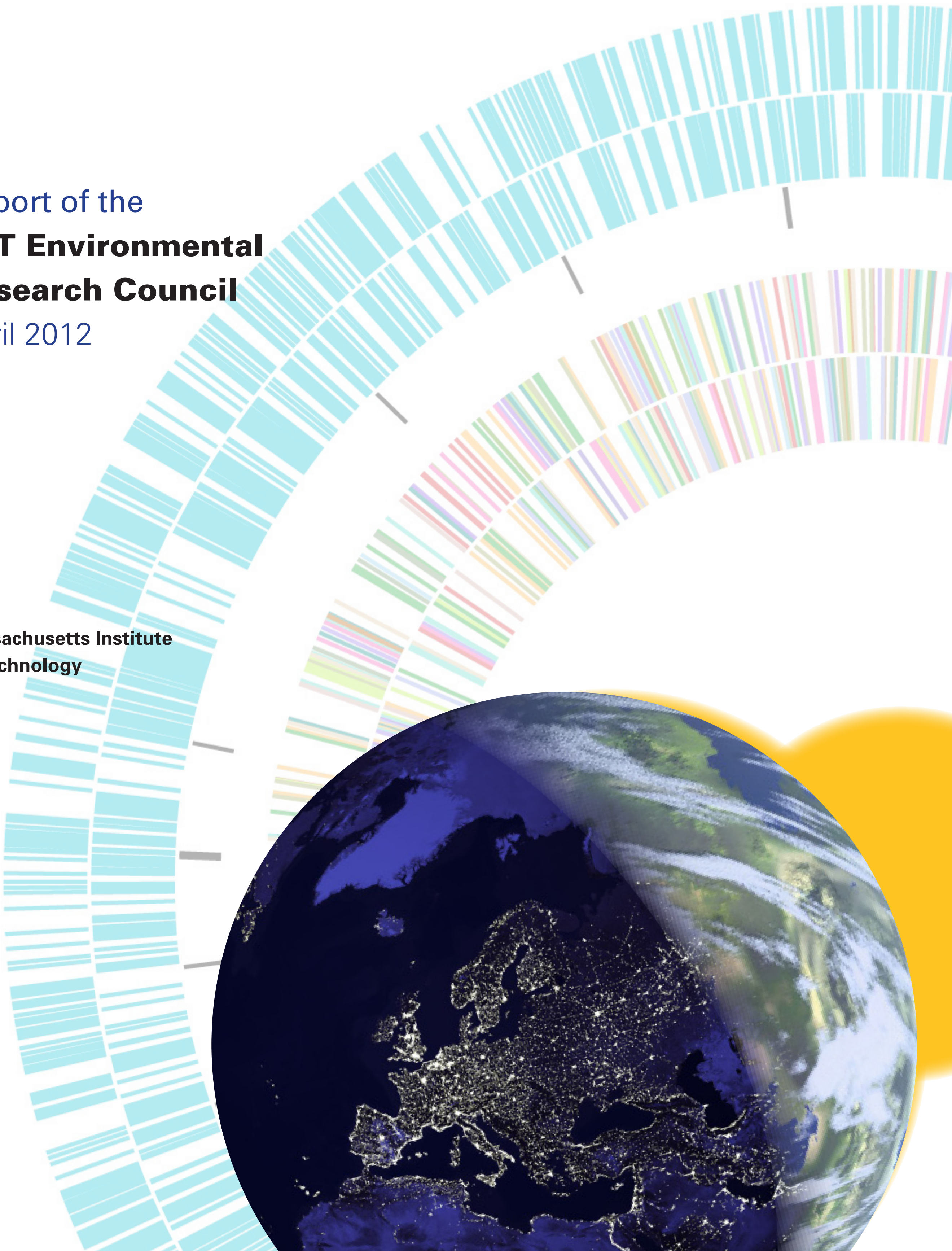
Implementing the **MIT Global Environment Initiative**

Report of the
MIT Environmental Research Council
April 2012



Massachusetts Institute of Technology

Cover Design:

Solar-powered co-evolution of life and Earth
A figurative sunrise brings another day of light and life to our world. The corona around the sun is the genome map of the marine bacterium *Prochlorococcus*—the most abundant photosynthetic cell on Earth. Meanwhile, pre-dawn Europe lies sharply defined by its dense web of urban illumination—a striking manifestation of the extent of human influence on the planet.

[Earth images courtesy of NASA; genome image courtesy of the Professor S. W. Chisholm Lab at MIT; Artist rendition by Tim Blackburn Design, Inc.]

Report of the Environmental Research Council:

Implementing the MIT Global Environment Initiative

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1. MIT Global Environment Initiative

The time is right for MIT to harness its renowned knowledge-building enterprise into a formal initiative focused on ensuring an environmentally sustainable future for humanity. The Environmental Research Council (ERC) therefore presents this implementation plan for the MIT Global Environment Initiative (GEI). The Initiative is dedicated to the rational management of our role on Earth through natural and social science-based strategies to promote resilience in both human and natural systems at local, regional and global scales. While ambitious, the enterprise outlined in this report is both appropriate and imperative for the Institute to pursue.

Grounded in the belief that scientific knowledge must inform how we choose to live on Earth, GEI will invigorate MIT's vital role as both a source of that knowledge, and of the engineering and social innovations needed to implement it. The overarching question driving GEI is: ***How can we enable sustainable human development?*** Finding answers and putting them to work is the mission of GEI, which will pursue a broadly integrated agenda of basic and applied research to inform real solutions for the real world.

Humans play an increasingly prominent role in shaping Earth's environment, with profound implications for our welfare and that of future generations. Acting to sustain the environmental systems on which we depend requires understanding how the biosphere works, just as knowledge of human physiology and genetics enables the practice of modern medicine.

This is the challenge to which the MIT Global Environment Initiative rises—integrating the Institute's core strengths in scientific, engineering and social research to better understand the global environment and manage our role in it through technological and social innovation.

In vision, design and implementation, GEI will be complementary to the MIT Energy Initiative (MITEI), insofar as many aspects of human impact on the environment are closely related to issues of energy. In less than five years since it was founded, MITEI has emerged as a thriving research and education enterprise of global reputation that has focused diverse talent from across the MIT on the challenges of energy production, delivery and use, and the environmental and energy polices associated with them. The new Global Environment Initiative, focused on understanding how our vital environmental systems function and the role humanity plays in them, will make close collaboration with MITEI a cornerstone of its approach to environmental knowledge building.

1.1 Why MIT? Why Now?

Since its founding in 1861, MIT has been committed to generating practical, science-based solutions to the grand challenges facing humanity. Now at the Institute's 150th anniversary, a trio of new challenges—human health, energy and the environment—demand the full dedication of our renowned research and education enterprise for the new millennium. With major initiatives well underway in energy and several areas of health science, the time has come for MIT to organize and formalize its thriving, but dispersed portfolio of environmental engagement through the Global Environmental Initiative.

World-class programs in many key disciplines—meteorology and oceanography, earth and environmental science, engineering and technology, life sciences and genomics, computation and modeling, economics, and social and policy analysis—coupled with a history of tackling the world's most pressing issues, already position MIT as a leader in developing novel approaches to restoring natural systems, and designing sustainable human systems embedded within them.

The implementation plan presented below comprises a roadmap for marshaling MIT's core strengths and cutting-edge research into a cooperative enterprise dedicated to informing the rational management of humanity's role on Earth. In keeping with growing momentum—from the birth of the Center for Global Change Science in 1990, to the launch of the Earth System Initiative in 2002, to the commitment to issues of energy and the environment in President Hockfield's 2005 inaugural address, to the launch of the Energy Initiative in 2006, to the report of the Committee to Assess Environmental Activities in 2007, to the founding of vibrant student group Sustainability@MIT in 2008—the ERC advocates creating GEI to focus and facilitate the inherent interdisciplinary creativity of MIT in a broad, but explicit agenda of impact-oriented environmental research.

In all, the combined leverage of GEI will greatly exceed that of its component parts to yield a major new player in environmental research arena, both at MIT and in the world, and we propose its creation with great optimism for a bright future.

1.2 Outline for Engagement

The overarching question driving GEI is: *How can we enable human development that is sustainable*? In response the Environmental Research Council (ERC) has focused on six of humanity's most pressing environmental challenges.

- ***Global Climate Change***: Greenhouse gas emissions affect Earth's chemistry, climate, weather patterns and ocean circulation in ways we are only beginning to understand. Global climate change threatens major disruptions to terrestrial and aquatic ecosystems, as well as human societies. What are the plausible trajectories of the global climate system, and what are the risks and uncertainties associated with each path? How can we better communicate those risks? And how can human societies both mitigate and adapt to the impacts of climate change?
- ***Health of the Oceans***: Overfishing, coastal runoff, habitat disruption, and acidification due to increasing concentrations of atmospheric carbon dioxide have markedly changed the world's oceans. Although oceans play a significant role in the climate system and provide vital ecological services, they are poorly understood and ineffectively governed. How have human activities affected the coastal zones and open ocean? How can we reduce our impact on the oceans through better management of coastal development, fishing, and other human activities?
- ***Fresh Water Supply***: We are rapidly depleting and degrading our vital fresh water supplies due to unsustainable practices—inefficient irrigation, water-intensive lifestyles and landscaping, groundwater use exceeding replenishment, contamination—and the simple reality of population growth. Already, some one

billion people lack reliable access to water, while two billion have inadequate sanitation. How does water circulate through the Earth system, and how are these cycles impacted by climate change? How can we better design households, landscapes, patterns of development and use, agricultural practices and industrial processes to conserve water? What clean water technologies can be developed and implemented effectively?

- ***Resilience of Ecosystems***: Ecosystems around the world are under pressure from harvesting, fragmentation, and changes in the water and biogeochemical cycles that sustain them. Many have already experienced major changes, and their future viability is uncertain. What attributes of ecosystems are most critical to their stability? How does biological diversity enhance ecological resilience in the face of natural and human-caused disturbances? How can we properly value ecosystem services so that they remain available to future generations?
- ***Environmental Contamination***: Synthetic chemical compounds are becoming ubiquitous in the environment and are accumulating rapidly. Contamination threatens to have both acute and chronic effects on human health and the environment, but those impacts remain poorly understood. What are the chronic and acute effects of exposure to different kinds of contaminants? How can we design chemicals, pharmaceuticals, materials, genetically-modified organisms, and production processes that are benign-by-design? And how can we mitigate the damage from harmful products already in circulation?
- ***Sustainability of Societies***: With global population and per capita consumption rising, the strain on Earth's natural systems can only increase. Meanwhile the world is urbanizing, presenting both challenges and opportunities for societies to become more sustainable. How can developing countries urbanize without exacerbating local and global environmental problems? Can restructuring of industries and markets, adjustments to supply chains, and the adoption of new production practices lead to improved corporate financial and environmental performance? Can we discover design features in natural ecosystems to help guide us toward sustainable human societies?

These, together with many other potentially dire and daunting environmental issues, define a vast problem space for environmental research. But while these challenges are enormous and pressing, so are the opportunities to confront them. Indeed, our scientific, technological and social capacities to examine, understand and modulate our effects on the environment are accelerating apace. These include, for example:

- Rapid advances in the life sciences and genomic technologies
- Exponential improvements in large-scale computational modeling capabilities
- Significant developments in complexity theory
- Unprecedented advances in sensitive yet affordable sensor technologies
- The emergence of an integrated systems approach to understanding both Earth processes and human societies
- Dramatic new capabilities in chemical, biological and materials design and synthesis

Taken together, these and other new capabilities promise to transform environmental science and management in much the same way that the science and practice of medicine have been revolutionized over the past half century through the advent of molecular biology and advanced imaging technologies. We face a historic challenge and opportunity to radically improve our understanding of how the global biosphere works, how human activities alter natural systems, how social, economic and political forces govern these environmental impacts, and how we prepare our students to pursue a sustainable future.

The Global Environment Initiative will adopt an inclusive approach that welcomes the participation of all interested faculty, research staff and students. Already, through an extensive process of Institute-wide inquiry and engagement, the ERC has begun to organize six areas of research momentum with which to launch the Initiative—*Climate, Oceans, Water, Ecological Resilience, Sustainable Societies and Contamination Mitigation*—These interrelated research themes (Figure 1.3) define an action agenda for GEI representing the convergence of MIT's strengths and potential with the suite of pressing global environmental challenges identified above.

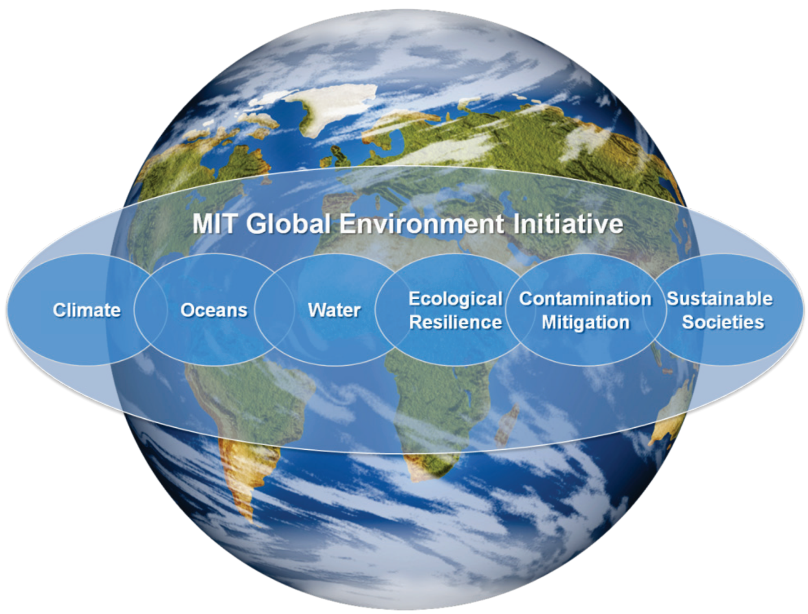

Figure 1.3 GEI as a cooperative enterprise of six inaugural research themes: Climate, Oceans, Water, Ecological Resilience, Contamination Mitigation and Sustainable Societies. Other themes and research priorities will be phased in as appropriate.

- ***Climate***: Scientists, engineers, and social scientists from across MIT are currently engaged in four climate-related programs: the Center for Global Change Science, the Joint Program on the Science and Policy of Climate Change, the Climate Modeling Initiative and the Lorenz Center. Taken together, they constitute a comprehensive foundation for understanding the climate system, its responses to human activity, and the policies for mitigation and adaptation. An emerging priority within this theme is to reduce the uncertainties of predicting climate variability and change in response to both natural cycles and human activity.

- ***Oceans***: In partnership with the Woods Hole Oceanographic Institute (WHOI), MIT has unparalleled capabilities in ocean observation and modeling, microbial oceanography, and the analysis of marine ecosystem dynamics. Researchers from MIT and WHOI are also investigating the impacts on coastal and marine ecosystems of urban development, fishery management, and other human activities. Priorities within this theme include understanding the role of oceans in climate and in global biogeochemical cycles, and detecting the impacts of global climate change, particularly sea-level rise and ocean acidification.
- ***Water***: Researchers at MIT aim to comprehend the impact of climate on regional water supplies, assess the consequences of chemical accumulation in fresh water systems, and lead in the development of clean water technologies. Designers at MIT are working to create landscapes that conserve water and restore regional aquatic ecosystems. Policy scholars are analyzing human impacts on regional water systems, and devising governance processes and policy mechanisms to mitigate and avert water shortages around the globe. Priorities within this theme include observing and understanding the role of water in the global environment, developing technologies and policies to ensure safe water supplies, and innovating in water-conserving landscape and urban design.
- ***Ecological Resilience***: Through an alliance between the physical and life sciences and engineering, MIT researchers are forging the new discipline of Modern Ecology, which focuses on the fundamental building blocks of ecological systems. One aim of modern ecology is to model the dynamics of ecosystems and understand the sources of their resilience. Another is to draw on advanced technologies and theoretical developments in order to decode "ecosystem genomes." Other research priorities include proper valuation of ecosystem services, and investigating the effectiveness of different strategies to conserve biodiversity in both developed and natural landscapes.
- ***Contamination Mitigation***: Research on contamination mitigation is embedded in diverse research labs scattered across the schools of Science and Engineering. Social scientists at MIT are also investigating the true costs of environmental contamination, as well as the effectiveness of policies aimed to discourage the use of harmful substances and processes. Significant potential for innovation in the science, engineering and practice of contamination remediation remains to be tapped, while an emerging area of priority research within this theme lies in developing 'benign-by-design' chemical, material, process and biological engineering practices to reduce the need for future remediation.
- ***Sustainable Societies***: Scholars from across MIT are working to enhance our understanding of how societies can become more sustainable. The School of Architecture and Planning boasts an international reputation for research on the design and governance of resilient cities. Researchers at the Sloan School of Management pursue pioneering work on environmentally sustainable business practices. Integrating these resources with those of the schools of Engineering, Science, and Humanities, Arts and Social Sciences, priorities within this theme include addressing the technical, managerial, economic, business, policy and cultural challenges of simultaneously optimizing human welfare and environmental sustainability.

These themes formed as a result of extensive engagement with the faculty through workshops, call for concept papers and other forms of inputs. The synergies across the various inputs were used to merge some of the ideas and form coherent themes that are focused but also relate and interact with each other in productive ways. The GEI research themes have different levels of initial organization and initial momentum. Ultimately how they develop will depend on the extent to which the faculty and research staff involved in them see value in new and multidisciplinary collaborations and commit to the research enterprise. As the research enterprises mature, there may be further aggregation and consolidation with new synergies identified. The number, focus and composition of the research themes will evolve as we learn more. An important role of GEI will be to facilitate communication and coordination within and among the themes. Furthermore, GEI will encourage the development of new research themes in response to emerging environmental challenges.

1.3 Research for Solutions

The ambitious research agenda presented above is motivated by and seeks to inform a wide array of pressing global environmental issues. Following the example of modern medicine, we advocate a revolution in environmental practice that is fueled by knowledge born of fundamental research, aimed at areas of critical need, and realized through engineering and social innovation. In other words, with environment as with human health, basic and applied research must merge to create the knowledge and capabilities that solve problems.

This "research for solutions" orientation is already well established at MIT across a broad range of scientific, engineering and social research relevant to the environment. Important new areas of integrated, impact-oriented research embraced by GEI include:

- Developing carbon mitigation technologies and assessing the potential of geoengineering schemes to produce desired results versus unintended consequences.
- Creating and deploying new sensing technologies to drive our understanding of Earth's oceans and how best to manage our use of and impact on them.
- Solving the riddle of affordable, equitable and sustainable global access to clean water through technological, economic and social innovation.
- Revealing the genetic and biogeochemical foundations of ecosystem function and resilience, and enabling strategies to restore and maintain the services they provide.
- Developing the technologies, practices and commitment to realize the environmental lifecycle benefits of benign-by-design materials and manufacturing.
- Exploring the sources, metrics and the very meaning of human welfare. How can it be optimized for societies and individuals across the world in a sustainable way?

1.4 Campus Involvement

While GEI's mission of enabling sustainable human development is fundamentally research driven and global in perspective, the essence of the organization itself lies in the community it creates at MIT. As such, GEI is inherently steeped in the educational mission of the Institute and committed to the broadest possible level of campus involvement. In this regard, the proposed initiative very much embodies the classic mantra "think globally, act locally."

Education, both curricular and experiential, is inseparable from the research enterprise of GEI, as it must be for any forward-looking organization committed to the creation, dissemination and application of knowledge. Experiential education—undergraduate, graduate and post-doctoral research mentoring—is integral to the research agenda of the initiative and its six themes, as amply demonstrated throughout Section 2 of this report and by the emphasis in Section 5 on the primary importance of funding for research fellowships. The commitment of GEI to supporting and developing curricular education is detailed in Section 3 of this report.

But full campus involvement for GEI will entail much more than its footprint in formal educational programs. A truly transformative community at MIT focused on environment and sustainability must embrace and exploit all the enthusiasm, initiative and creative energy on campus—particularly from students, our greatest resource.

The commitment of MIT students to issues of global environment and sustainability is well established and constantly evolving. In the 1980s, the undergraduate group SAVE (Share a Vital Earth) was the driving force behind the Institute's now thriving annual Earth Day celebrations. Eventually, SAVE merged with Students for Global Sustainability and several other groups to form Sustainability@MIT, now a thriving hub of combined undergraduate and graduate student activity that sponsors an annual Sustainability Summit with a national reputation. In 2005, engineering and management students cooperated in creating The Generator, a biannual event fostering collaboration and innovation in energy, environment and sustainability. More recently, student governance at both the undergraduate and graduate levels established highly active subcommittees focused on sustainability. Students are also active in MIT's Campus Sustainability Program through the Green Ambassadors Initiative and representation on the Campus Energy ("Walk the Talk") Task Force.

Embracing and partnering with these and other organizations and activities on campus will be a major emphasis for GEI as it evolves. Priority areas for involvement will include:

- Engaging students in the planning and implementation of GEI
- Supporting MIT's efforts to lead by example through efforts like *Walk the Talk*
- Helping promote curricular and extracurricular opportunities to use MIT as a "living laboratory" of sustainability
- Providing a central forum for engaging the entire MIT community

1.5 Details of the ERC Process

This ERC implementation plan for the Global Environment Initiative represents a major milestone in a broadly inclusive Institute-wide process to identify areas of endeavor defined by the convergence of pressing global environmental challenges with existing and emerging research expertise and faculty interest at MIT. This process formally began with the Committee to Assess Environmental Activities at MIT, convened by Provost L. Rafael Reif and Chancellor Phillip L. Clay in early 2007. Appendix attachments A1 through A7 chronicle the history of this process—from the original charge to the assessment committee chaired by Professor Maria Zuber (A1) to the release on May 20th, 2010 of the ERC's first report *Prospectus for an Initiative on Global Environment at MIT* (A7).

Like the "Zuber Committee" before it (A3), the ERC has striven to engage the MIT community, soliciting input from across the Institute in formulating an ambitious, but grounded environmental research agenda. Important events in the ERC process have included:

- Sponsoring *Rethinking Water: A Critical Resource*. This full-day "workshop to advance water research and teaching at MIT" was held on May 21, 2010, the day after the ERC Prospectus Report was released. MIT President Susan Hockfield opened the workshop and emphasized the imperative of engaging our research enterprise in addressing the critical environmental challenges before us. The priority research areas for the Water theme detailed in this report grew out of this workshop's agenda (A8)
- Co-sponsoring *The Future of the Oceans: Building a New Agenda for Ocean Research and Education*. This full-day workshop and follow-on strategic planning session (A9) substantially involved the Woods Hole Oceanographic Institution (WHOI) and led to the formulation of the Oceans theme and its priority research agenda
- Participation in a widely attended planning meeting on new directions for climate science at MIT. This event, hosted by Professor Ronald G. Prinn, Director of the Center for Global Change Science and the Joint Program for the Science and Policy of Global Change, led to the development of the Climate theme and the identification of its priority research agenda
- Placing an Institute-wide call for environmentally oriented research concept papers to inform the implementation planning and identify thought leaders committed to material participation in the GEI. Eighteen multi-author concept papers were received (A10) and augmented with other equally substantial, though less formal input gathered from faculty and research staff

The result these and other outreach activities is this proposal to implement GEI based on six essential themes of research that will "build strength on strength," as detailed below.

2. Initial Research Agenda: Building Strength on Strength

Over the past few decades, the focus of MIT's core research strengths relevant to issues of the environment has evolved and expanded in concert with growing faculty commitment to the perspectives of global change and Earth system science. Indeed MIT today is a global hotspot of environmental research, even though the Institute is not particularly well known for these strengths. That environmental research at MIT has been "flying under the radar" is a direct consequence of the Institute's greatest strength—the inherently individualistic and collaborative nature of its faculty. MIT is an enormously successful generator of innovative, cross-disciplinary sponsored research at the grassroots level of individual faculty. However, in the absence of any formal, Institute-wide mechanism for building communication and community across the relevant fields, the wealth of active research can end up dispersed and disjointed. Such has been the case with environmental research at MIT—until now.

With GEI we aim to do for environmental research at MIT what MITEI has done for energy research—build strength on strength by enhancing an existing, though scattered research enterprise through organization, facilitation, communication and strategic support with a clear emphasis on:

- Leveraging synergies
- Exploiting efficiencies
- Cultivating faculty engagement
- Incubating cross-disciplinary collaboration
- Nurturing new areas of priority research

This is what building strength on strength means—harnessing what MIT faculty and research staff want to offer in the realm of environment and magnifying it through coherent organization into a unified, but still adaptive and inclusive enterprise, which is greater than the sum of its parts and clearly focused on developing new directions for priority research. New directions for priority research in GEI's foundational themes include:

- *Climate*—reducing the uncertainty in climate change projections
- *Oceans*—understanding the implications of global change (e.g. sea level rise and ocean acidification) and developing new observation technologies to enable ocean science and engineering
- *Water*—developing practical technologies for clean water, assessing the outlook for water in a changing global environment, and improving design for water in landscapes and societies
- *Ecological Resilience*—revolutionizing our understanding of the design and function of ecosystems through the physical and life sciences empowered by engineering
- *Contamination Mitigation*—creating the knowledge and tools to enable benign-by-design chemical, material, process and biological engineering

- *Sustainable Societies*—developing the data, theories and tools to understand and optimize the balance between human welfare and environmental sustainability at every scale

We recognize that the challenges of global climate change, health of the oceans, fresh water supply, resilience of ecosystems, sustainability of societies, and environmental contamination are both complex and interrelated. For example: climate change influences and is influenced by oceanic processes; climate change also affects ecosystems and the global water cycle; and as cities strive to reduce their carbon footprint, improve their air quality and prepare for sea-level rise, a radical rethinking of urban design is underway. Similarly, contamination reduces available clean water supplies, damages ecosystems, and affects the habitability of vast swaths of urban land.

Addressing these urgent and fundamentally related challenges will require deep scientific understanding of the interactions that comprise the global environment; creativity in devising behavioral and technological solutions; and a clear-eyed sense of the economic and political obstacles to adopting and implementing those solutions. With its interdisciplinary, problem-solving culture, MIT is well-positioned to undertake an initiative that demands such an integrated approach.

2.1 Climate

Human activity is now precipitating changes in the global climate at rates approaching or exceeding those of natural perturbations and shifts throughout human history. The eventual response of the climate system to our actions remains uncertain, mostly because we are only now beginning to comprehend the intricate feedback mechanisms that can either buffer or destabilize the system. We thus face an urgent need to build our basic scientific understanding and predictive capability of how Earth's climate system functions and responds to varying scenarios of human impact and natural forcing. Understanding and predicting global climate change is arguably the most complex scientific challenge ever faced by mankind. Almost everything has the potential to affect climate—from microscopic aerosol particles to greenhouse gases to plankton to sea ice to land use. The climate system thus consists of many interacting components forming a highly nonlinear system of enormous complexity.

The international focus upon climate change science has become acute due to intensifying global climate warming linked to increasing atmospheric greenhouse gas concentrations and land-use changes. Model calculations of the future trajectory of Earth's climate are therefore being subjected to increasing scrutiny. Fundamental uncertainty underlies all climate models because the processes that determine climate sensitivity involve interaction and feedbacks between key components that remain mysterious and require interdisciplinary research to understand: principally clouds, water vapor, convection, land and sea ice, oceans, ecosystems and the aerosol and carbon cycles.

Indeed, the unacceptably wide range of uncertainties that characterize the increasingly complex and numerous "Earth System" models being employed to make global climate projections is attributable to this fundamental lack of understanding. Various symptoms of the importance of this issue are now clearly recognizable and must be resolved if uncertainties concerning the expected degree of future global warming and its regional impacts are to be reduced. It is imperative that we quickly build up our basic scientific understanding of how the climate system has functioned over time, encapsulate that understanding in models, and thereby bolster our ability to project climate response to the joint influences of human and natural forcing. This research must necessarily be interdisciplinary and furthermore integrate the human and natural components of the climate system to address the key policy-relevant issues of climate impacts, mitigation, and adaptation. It is also important to foster research into methods for decision-making under uncertainty and public communication of risk to advise and facilitate the policy-making process in climate.

2.1.1 Opportunity at MIT

Given the pressing need to understand, forecast and mitigate global climate change, it is imperative that MIT organize and enhance its already world-class capabilities in climate science to lead the way in meeting this challenge—perhaps the greatest facing humanity today. The primary goal GEI with its Climate theme will be to coordinate interdisciplinary activities that build fundamental understanding of how Earth's climate system works, represent and quantify that understanding in models, decrease uncertainty related to climate change, and foster intelligent, science-based climate policies.

With a strong foundation of well-established key players in place (Figure 2.1) GEI is poised to make rapid progress through its Climate theme over a broad agenda of critical research at the frontiers of climate science. These include: the roles of the oceans and cryosphere in past, present and likely future climate; the relationships of water, ecosystems and biogeochemical cycles to climate; new observing systems and models that couple the roles of aerosols, convection and clouds in the climate system; the links between climate, air quality and human health; the co-evolution of life and climate; the insights to be learned from observing "exo-climates" on other planets; the impacts of human activity—particularly in altering biogeochemical cycles and land use—on climate; and, critically, the effective translation of climate science knowledge into policy engagement and risk communication.

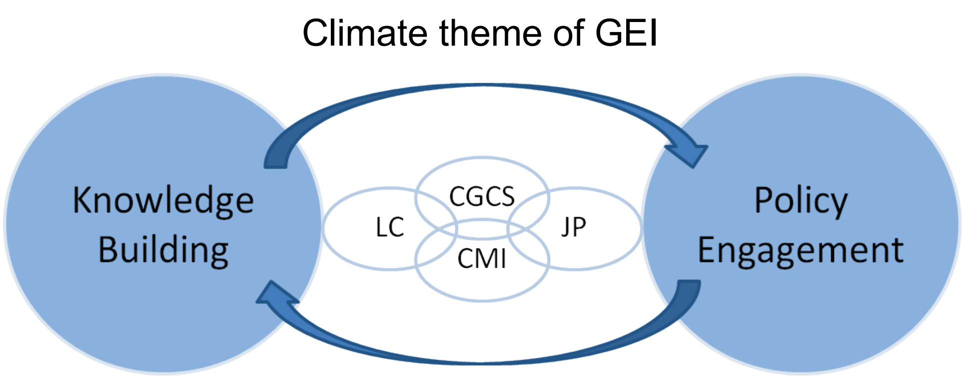

Figure 2.1 Through its Climate theme, GEI will coordinate relevant activities at MIT to build a two-way bridge between the knowledge building of fundamental research in climate science and the policy engagement vital to bringing knowledge into action (LC = Lorenz Center, CGCS = Center for Global Change Science, CMI = Climate Modeling Initiative, JP = Joint Program on the Science and Policy of Climate Change).

The activities of GEI within its Climate theme will add significant value to climate studies at MIT. Specifically, it will: formalize and streamline coordination amongst existing climate-related programs at MIT; identify new priority areas for interdisciplinary research; provide a formal and cohesive mechanism to enhance the already strong interactions between climate studies and the broader spectrum of activities in environment, energy and policy at MIT; and assist all theme participants in their communications with the public, and with potential donors to and sponsors of research in both climate and the full range of research within GEI. The Climate theme represents a key area of cooperation between GEI and MITEI, and naturally it will also generate enhanced educational opportunities across MIT.

Simply put, activity under GEI's Climate theme will focus and enhance the Institute's formidable capabilities in climate research, and build bridges to the highly talented pool of expertise available in the Greater Boston region. With world-class programs in all of the key disciplines—earth, atmospheric and ocean sciences; engineering and technology; computation and modeling; economics, management and decision making; and policy analysis and design—MIT is the ideal institution to lead the way in addressing the climate challenge.

2.1.2 Research Priorities

The research priorities for the Climate theme follow directly from the stated purpose to "...coordinate all activities that build fundamental understanding of how Earth's climate system works, represent and quantify that understanding in models, decrease uncertainty related to climate change, and foster intelligent, science-based climate policies." As such, the plan outlined below is arranged into ten major thrusts of fundamental, long-term research effort, each of which will be pursued through a practical agenda of new targeted research priorities that will evolve as appropriate over time:

- Oceans in the Climate System
- Water and Climate
- Role of the Cryosphere in Climate
- Co-evolution of Life and Climate Over Earth History
- Biogeochemical Cycles and Climate
- Aerosols, Convection and Clouds
- Climate, Air Quality and Human Health
- Learning from Exo-climates
- The Integrated Climate System
- Climate Policy and Risk Communication

Oceans in the Climate System

The climate of Earth is, to a large degree, shaped by the presence of the global ocean. Indeed the ocean, and life within it, is largely responsible for the world as we know it—setting the concentration of many gases within our atmosphere, acting as a climate thermostat and influencing the transformation of energy, water and carbon within the climate system. Our ability to understand the paleo-climate record, and anticipate what might happen to earth's climate in the future, depends on our understanding of the role of the ocean in climate.

Key research questions to be addressed include:

- What causes the deep meridional overturning of the ocean that today accounts for roughly one third of the net ocean-atmosphere heat transport from the equator toward Earth's poles?
- What is the essential nature of the coupling between the oceans, atmosphere, cryosphere and land surface processes—modulated by Milankovitch forcing and biogeochemical cycles—that leads to ice ages?
- What controls the rate at which the ocean sequesters heat and carbon from its interface with the atmosphere into its interior, and what are the implications for the future trajectory of the earth under global warming?

This priority research thrust represents an area of synergy with the Oceans theme. The focus here is on the interface between climate and ocean and the role of the oceans in modulating the climate system. The related research thrust in the Oceans theme—*Role of Oceans in Global Climate and Climate Change*—is focused on enhanced observation and modeling (see Section 2.2.2).

Water and Climate

The total amount and distribution of water in the atmosphere is very sensitive to temperature such that global warming is expected to lead to substantial changes in all aspects of the water cycle from local to global, and seasonal to decadal scales. Understanding and anticipating the vulnerability of critical water resources and the potential impacts on human welfare will encompass the full complexity of the water cycle over land. The scientific challenges span the full range of spatial and temporal scales, from microphysical processes such as the effects of aerosols, to large-scale changes in radiative forcing of climate and atmospheric circulation. Progress will come both from improved observational and modeling capabilities, and improved understanding of global water cycle dynamics.

Key research questions to be addressed include:

- Do precipitation extremes (e.g. storminess, tropical cyclones, floods and droughts) respond to climate change primarily through increased water vapor in the atmosphere, or do circulation changes also matter? For example, do blocking events occur more of less frequently in a warmer climate?
- How can we better constrain the different effects of aerosols on precipitation patterns?
- At what rate does global-mean precipitation increase under warming, and is there a maximum value that can be achieved through greenhouse warming?
- How can we better use proxies for the water cycle in past climates to gain a better understanding of important climatic features such as the monsoons and the locations of the desert belts?

- How does the water cycle over land respond to climate change? For example, how important are soil moisture feedbacks for changes in continental precipitation patterns?
- How would the water cycle respond to a possible future stabilization or reduction in greenhouse gas concentrations, and how would it respond to a geoengineering scheme that offsets greenhouse-gas-induced warming?

This research thrust links to the *Water in a Changing Global Climate* research thrust of the Water theme (see Section 2.3.2). The focus of the activity here is on understanding and predicting changes in the water cycle embedded in the climate system. The complementary activity within the Water theme will draw from these results in assessing the implications for freshwater resources critical to human society and our hydraulic infrastructure.

Role of the Cryosphere in Climate

The cryosphere—global snow and ice—is one of the least understood components of the climate system in terms of observations, theory and comprehensive modeling capabilities. It is also the component that has exhibited the most rapid and apparent changes over the last few decades. From a climate perspective, polar amplification (e.g. the above-average increase in Arctic near-surface temperatures) is a robust feature in climate model projections. However, the underlying causes of the amplification in general, and Arctic sea ice decline in particular, remain poorly understood and are not well predicted by climate models. The impacts on land snow cover and the feedback of changing snow cover on climate dynamics are highly uncertain. Also, the role of the polar oceans in present and future carbon uptake also remains poorly quantified.

Key research questions to be addressed include:

- How can the uncertainties in projections of the extent of polar ice sheets, sea ice persistence and sea level change be reduced?
- How do driving processes vary between the Arctic and Antarctic and what are the consequences for climate change?
- What role do the great polar ice sheets play in the climate system, both in terms of its relative stability on human time scales and its tendency toward cyclic variability over geologic time?
- Is the abundant presence of solid-phase water on Earth's surface as both land and sea ice critical to the system's conjectured ability to support multiple equilibrium climate states for a given intensity of radiative forcing?

This research thrust on the cryosphere represents a strong link between the Climate and Oceans themes. The complementary research thrust within the Oceans theme focuses on the implications for polar ocean resources, and observing sea-ice and polar engineering (see Section 2.2.2).

Co-evolution of Life and Climate over Earth History

Abundant modern and geological evidence attests to the vital role of marine and terrestrial ecosystems in the evolution and current functioning of Earth's climate system. From the abundance of free oxygen in the atmosphere, to the variable albedos of land and sea, and to the heterogeneity of the hydrologic cycle, biological systems—including humanity—clearly matter. By the same token, ecosystems are significantly affected by climate. Comprehending these intimate relationships is of critical importance to understanding both the causes and consequences of climate change.

Key research questions to be addressed include:

- What essential physical, biological, chemical and dynamical processes dictate the overall interaction of Earth's biosphere with its climate system?
- Which are the dominant ecosystems that influence and are influenced by the climate system, and how does this relationship vary between them?
- How do anthropogenic land use changes impact the climate and global carbon budget?

This research thrust under the Climate theme represents a major area of synergy with the Ecological Resilience theme—the co-evolution of biotic and abiotic components of both marine and terrestrial ecosystems (see Section 2.4.2).

Biogeochemical Cycles and Climate

Life and climate are intimately connected through the cycling of elements present in both living tissue and the radiatively active gases in the atmosphere. For example, the partitioning of carbon between atmospheric CO_2 and inorganic forms in water and sediments is strongly modulated by living creatures. The biogeochemical cycles of carbon and other important elements such as nitrogen, phosphorus, sulfur and iron are now being massively perturbed by human activity in ways we are only beginning to appreciate. By any measure, there remains a great deal to learn in identifying and understanding the primary biogeochemical cycles that affect the climate system.

Key research questions to be addressed include:

- What are the biological, chemical and dynamical processes that control the partitioning of carbon between the oceans, land and atmosphere?
- Why does global mean temperature co-vary so closely with the concentration of atmospheric CO_2 , CH_4 and N_2O in the recent geological past, and what are the implications for the anthropogenic forcing of climate?
- How will the anthropogenic perturbation of the nitrogen and phosphorus cycles affect terrestrial vegetation, and modulate marine productivity and ecosystems, particularly near ocean margins?
- How does the biologically mediated marine sulfur cycle interact with the atmosphere and climate?
- Can we characterize and understand the cycles of biologically important trace metals (e.g. iron) in the oceans, how they have changed in the past, and how they might change with human activity?
- What controls the terrestrial sources and atmospheric sinks of methane and similarly of other non-CO_2 greenhouse gases and how are they being affected by human activity?

This research thrust under the Climate theme represents another area of distinct synergy with the Ecological Resilience theme—the role of microbiomes and terrestrial ecosystems in the global biogeochemical system (see Section 2.4.2).

Aerosols, Convection and Clouds

The most important radiatively active components of the atmosphere are water vapor and so-called layer clouds, which contribute to cooling by reflecting solar radiation (i.e. increasing albedo) and contribute to heating by absorbing and re-emitting infrared radiation from Earth's surface (i.e. the "greenhouse effect"). Nonetheless, atmospheric convection and the distribution and dynamics of clouds remain major uncertainties in climate modeling, especially for low-level clouds that affect both climate sensitivity and atmosphere-ocean coupling. While aerosols also play a direct role in both reflecting and absorbing solar and infrared radiation, they are even more important as the condensation nuclei upon which all water cloud formation depends. Given the potential deployment of atmospheric aerosol manipulation schemes to "geoengineer" climate, better understanding of convection, clouds and the role of aerosols is essential.

Key research questions to be addressed include:

- What determines the spatial-temporal spectrum of atmospheric convection?
- What large-scale processes other than atmospheric convection influence cloud distribution and attributes?
- What controls the availability—production, distribution, persistence and suitability—of aerosols to act as cloud condensation nuclei?
- What chemical and physical processes control the availability—production, distribution, persistence and suitability—of aerosols to act as cloud condensation nuclei?

Climate, Air Quality and Human Health

Climate and air quality (on the local, regional, and global scales) are intimately connected: climate both affects and is affected by the concentrations of pollutant species that have an adverse impact on human health. Increased emissions or secondary production of such pollutants can drive changes to climate, since species such as ozone, soot, and fine particulate matter are all strong radiative forcers. Changes to climate, in turn, can play a major role in air quality, by affecting the rates of emission, chemical transformation, and deposition of pollutant species. The detailed linkages between these two topics of great societal concern are, however, very poorly understood at present.

Key research issues to be addressed include:

- What are the models and laboratory treatments of air pollutant transport and transformation that can predict air quality on the local, regional, and global scales?
- How can we obtain higher-resolution spatial and temporal measurements of pollutant concentrations within local or regional environments (incubates the environmental sensing research thrust of the Ecological Resilience theme)?
- What are the formation and effects of climate-relevant secondary air contaminants (ozone and aerosol) created by the chemical transformation of primary emissions?

- What are the relationships between pollutant concentrations, human exposure, and human health?
- What are the feedbacks between emissions of key species (organics, sulfur compounds, etc.) and regional/global climate?
- How does local (urban) air quality affect and get affected by air quality and climate on the larger regional and global scales? What are the potential implications of climate change?

Learning from Exo-climates

Looking beyond Earth, comparative planetology can provide insights on climate processes through study of other planets that have, or have had atmospheres. For example, our near neighbors Venus and Mars provide a striking contrast in planetary evolution—a “runaway” greenhouse and a nearly complete loss of atmosphere, respectively. Furthermore, the discovery of new “exo-planets” orbiting distant stars and showing evidence of “exo-climates” is providing a broader and deeper context within which to understand the fundamental processes of climate system dynamics and the co-evolution of life and climate.

Key research questions to be addressed include:

- How common is the “Goldilocks Zone,” the combination of surface temperature and pressure amenable to carbon-based life on a planet that orbits a main sequence star such as our Sun?
- How do significant changes in a planet's inclination, orbital eccentricity, or continental arrangement change climate by way of atmospheric or oceanic dynamics? Are the fundamental physical processes different or similar to Earth's?
- What physical and/or chemical phenomena drive a terrestrial planet beyond a threshold into an extreme state such as a "snowball" state or “runaway” greenhouse?
- What greenhouse gases are or might be present on other planets, and how are the climates of those planets impacted?
- Can we understand cloud and aerosol formation well enough from first principles to understand cloud formation on other planets?

The Integrated Climate System

The complete climate system involves all of the fundamental research areas described above, and their interactions. Thus, understanding overall climate behavior demands integrating our understanding of multiple complex phenomena spanning diverse space and time scales, which is itself an important research challenge.

There are two logical parts to this integration; we need to understand the climate system both with and without human influence and test the theory and models developed using post-industrial and pre-industrial observations. Integrated climate system models that address the natural system, and the coupled natural and human systems are therefore essential cornerstones of the Climate theme. These models will range from heuristic to intermediate complexity to full complexity depending on the questions being addressed. Such a hierarchy of models, being developed by the CMI and CGCS, will collectively form a comprehensive research tool for analyzing natural climate variability and realized and potential anthropogenic climate change and its social and environmental consequences. This approach should allow for study of the sensitivities and uncertainties that are crucial to policy evaluation, and provide an analytical tool for simulating local through global climate changes to compare with observations and inform local decisions regarding adaptation. Equally important, it should be a vehicle to recognize the gaps in knowledge of the natural and human components of the climate system not yet able to be encapsulated in integrated models, and thus to spur research in each of the preceding fundamental climate research areas. This integrative activity has an additional practical bonus; it forms a vehicle for the needed interdisciplinary interactions since it engages almost everyone involved in these fundamental areas through its intellectual formulation, as well as the majority through its realization.

Climate Policy and Risk Communication

Many human activities have the potential to influence climate, for example greenhouse gas and aerosol emissions, air pollution, and patterns and types of land-use—particularly agriculture and urbanization. At the same time, the impacts of climate change can substantially influence human well-being and behavior. Also increasingly evident are the problems created by the complexities and uncertainties of potential efforts to control human influence on the atmosphere, land and oceans. For example, measures to limit greenhouse gas emissions are intertwined with major segments of both the modern industrial economy and more traditional agriculture and forestry. Thus climate policy cannot be separated from issues of tax structure, international trade regimes, agricultural policy, energy security and conservation initiatives, and other environmental concerns such as urban air pollution and the appropriate role of nuclear power. Moreover, any long-term emissions control agreement inevitably raises questions of international equity, most importantly between the current industrial economies and the developing nations. Understanding and quantifying the economic and cultural drivers of these human activities, and the mechanisms and costs of mitigation and adaptation, are important goals for climate research.

Building upon the Joint Program on the Science and Policy of Global Change, a successful program of research and education regarding climate should therefore include the integration of the social science, natural science and engineering aspects of human activities and their implications for multiple climate effects. Given the uncertainties and complexities of the climate issue, research under GEI's Climate theme will include decision-making under uncertainty, and effective strategies for communicating risk-based analyses of the scientific and economic issues to policymakers and the general public. In this way, the research enterprise will strive to produce careful analyses relevant to ongoing national and international environmental policy debates, and effectively communicate its results to the wider research community, policymakers and the public so as to have a positive impact.

2.1.3 Organization and Development

At its foundation, the Climate theme of GEI builds on an alliance of four existing programs at MIT: the Center for Global Change Science (CGCS); the Joint Program on the

Science and Policy of Global Change (JP); the Climate Modeling Initiative (CMI); and the newly formed Lorenz Initiative (LI) [1]. As illustrated in Figure 2.1, the purpose of GEI's activity under the Climate theme will be to coordinate and enhance the work of these affiliated programs, with the anticipation that other organizations and individual researchers will join over time. In particular, close relations are anticipated with the Department of Earth, Atmospheric and Planetary Sciences and its Program in Atmospheres, Oceans and Climate, the Department of Civil and Environmental Engineering and its Parsons Laboratory for Environmental Science and Engineering, the Woods Hole Oceanographic Institution (WHOI) through the MIT-WHOI Joint Program, and the MIT Energy Initiative. In the meantime, the four founding programs are described briefly below.

While research and education activities within GEI's Climate theme will launch with the significant momentum and resources of these founding organizations, additional resources will be needed to realize their full potential. Necessary support for new programs common to all GEI themes includes: graduate and post-doctoral fellowships, undergraduate research opportunities, ignition grants, visiting faculty, essential facilitative administrative support, and targeted community-building and outreach activities. Activities within GEI's Climate theme also need special support to:

- Attract climate modelers and numerical/computer specialists to develop an atmospheric model to incorporate innovations in parameterizations of convection, clouds, atmospheric chemistry and aerosols, and to couple to existing land and ocean models for climate research. This activity would be overseen by the CMI and also become part of CGCS's Integrated Global System Model

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[1] *The MIT Center for Global Change Science* (http://web.mit.edu/cgcs/www/) addresses fundamental questions about environmental and climate processes with a multidisciplinary approach. The Center's goal is to improve the ability to accurately predict changes in the global environment. It seeks to better understand the natural mechanisms in ocean, atmosphere and land systems that together control the Earth's climate, and to apply improved knowledge to problems of predicting climate changes. The Center utilizes theory, observations, and numerical models to investigate climate phenomena, the linkages among them, and their potential feedbacks in a changing climate. It focuses on large projects that require the cooperation of multiple investigators and disciplines. Founded by its current director Professor Ronald Prinn in 1990, CGCS currently includes 22 affiliated faculty and eight research scientists.

The Joint Program on the Science and Policy of Global Change (http://globalchange.mit.edu/) conducts research and analysis on issues of global environmental change, in particular climate, and communicates results to the research community, policymakers and the public. The Program focuses on the integration of natural and social science aspects of the climate issue, to produce analyses relevant to ongoing national and international policy debates. Combining the efforts of CGCS with MIT's Center for Energy and Environmental Policy Research, the Program is distinguished by its central activity—the Integrated Global System Model—which addresses coupled economic, technological and environmental change to provide a comprehensive tool for analyzing anthropogenic environmental changes and their social consequences. Cofounded in 1991 by Professors Ronald Prinn and Henry Jacoby, the Joint Program includes 19 affiliated faculty and five research scientists.

The Climate Modeling Initiative (http://paoc.mit.edu/cmi/) is a collaboration of scientists developing and refining modeling infrastructures for the study of the atmosphere, ocean and climate of the Earth. An approach emphasizing modeling hierarchies is pursued, bridging from simple to complex, but based on a common set of methods encompassing algorithmic, computational, physical, biogeochemical and technological innovations, and drawing together elements of computational fluid dynamics, statistics, meteorology, oceanography and computer science. Its models are now widely used in support of science and policy at MIT, and at many other research institutions around the world. Founded in1996 by Professors John Marshall and Peter Stone, CMI includes eight affiliated faculty, and four research scientists and engineers.

The Lorenz Center, newly founded in 2010 by co-directors professors Kerry Emanuel and Daniel Rothman, will soon provide a select and diverse group of exceptional faculty, research scientists postdoctoral fellows and students with the freedom and resources to think "outside the box" and pursue innovative, high-risk paths toward a better fundamental, theoretical and mechanistic understanding of how Earth's climate system works. In focusing on the enormous challenge of piercing the apparent complexity of the climate system to comprehend the essential physics, chemistry and biology that drive it, the Lorenz Center aims to become the world's pre-eminent center for climate study as a curiosity-driven intellectual challenge.

- Co-fund (with federal agencies) the acquisition of innovative biogeochemical, trace gas and aerosol instrumentation and computational equipment, which will enhance the biogeochemical cycles, aerosol-cloud interactions, and climate system modeling research priorities while providing a valuable training facilities for students

Note that the resources needs detailed above are in addition to those already being sought to support the Lorenz Center, for which official fund-raising efforts have begun.

Finally, faculty development in certain priority areas of research expertise would also enhance the ability of activities within GEI's Climate theme to reach their full potential. These areas include:

- *Climate Theory and Modeling*—observation, theory and modeling of the atmosphere's past and present climates; Understanding the influence of biogeochemical and water cycles on the climate system through analysis, observations and modeling reduces the uncertainty of climate response to natural and anthropogenic forcing
- *Cryospheric Sciences*—the observation, dynamics, theory and modeling of water in its solid phase on Earth, including: sea ice, the polar ice sheets, mountain glaciers and icecaps, permafrost soils and snow-related processes. The cryosphere remains among the least understood, yet potentially most important components of the global coupled climate system.

2.2 Oceans

Earth's oceans represent its final frontier. Very little is known about the oceans relative to our world on land. The impact of climate change and human activities on the oceans, however, is real and poses significant physical, ecological, social and economic challenges for humankind. Ocean surface waters are warming, sea level is projected to rise over the coming century to threaten coastal communities, the oceans are becoming increasingly acidic, and marine habitats are under threat. Human activities are compromising the health of the oceans and hence their ability to sustain themselves and us, with implications for fishing, shipping, tourism, offshore resource exploration and extraction, and ocean governance. The challenge is to understand critical aspects of our oceans today including sea-level rise, declining marine habitats and fisheries, reduced seasonal sea-ice coverage, ocean acidification and pollution, and the huge role oceans play in global climate.

2.2.1 Opportunity at MIT

MIT, in close partnership with WHOI, is well positioned to establish a hub of coordinated and focused ocean research. On December 2, 2010, well over 100 MIT faculty from diverse departments and WHOI scientists participated in a special ERC co-sponsored workshop to launch this effort—*The Future of the Oceans: Building a New Agenda for Oceans Research and Education*. This workshop represented nearly every major aspect of ocean science, engineering and technology. Understanding how the ocean will evolve in the future demands a coordinated study of its physical, chemical and biological aspects; developing new methods and technologies to better sense and predict the ocean processes; and developing procedures to better manage its use as a source of food, energy, transportation and recreation.

Together, MIT and WHOI have a strong history and outstanding complementary capabilities in developing:

- Novel ocean sensing technologies for probing marine biological, chemical and physical processes, and applying such technologies in ocean exploration and observation
- Connections between ocean ecology and human health
- Models of ocean circulation and biogeochemical cycles constrained by observations and configured for state estimation and prediction
- New technologies to improve safety and reduce pollution in transportation, and minerals extraction
- New management procedures to better utilize the oceans

Activities in Oceans span a wide range of academic units at MIT, including the Department of Mechanical Engineering's Center for Ocean Engineering, the Department of Civil and Environmental Engineering's Parson's Laboratory for Environmental Science and Engineering, the Program in Atmospheres, Oceans and Climate in the Department of Earth, Atmosphere and Planetary Sciences, faculty in the Department of Electrical Engineering and Computer Science and the Sloan School of Management, and the Joint MIT-WHOI Program. Moreover, in collaboration with WHOI, we have a longstanding and highly successful graduate educational program—the MIT/WHOI Joint Program. Over its 40 year history, the Joint Program has graduated many hundreds of graduate students in Oceanography, many of whom are now leaders in the field working in institutions all over the world.

Between them, MIT and WHOI have more than 100 senior oceans science and technology researchers who together span the entire space of disciplines, scales and processes needed to address the issue of the oceans' future. A significant benefit of the Oceans theme within GEI will be to enable ocean researchers from around MIT and WHOI to develop focused research initiatives that cover the broad range of interdisciplinary topics needed to address the most pressing problems now facing the world's oceans. Cross-fertilization between different sensing groups and modelers will lead to new technology applications and new insights from novel observations.

The impact of implementing the research agenda of GEI's Oceans theme will be immense. There are huge benefits to be reaped from increased interaction between scientists and engineers, as new sensing and monitoring technologies drive innovations in observation and modeling, which will in turn enable improved decision making and intervention. Yet this vision needs an organizational unit that facilitates interactions and brings together the various disciplines in an organized manner. Moreover, by formulating a vision and spelling out concrete needs, researchers around MIT who are not currently involved in ocean research may realize the potential for contribution. A huge gain in productivity and an accelerated response can result from a coherent overall approach to solve the problems currently facing the oceans. These problems span disciplines and scales, and demand a newly integrated approach of the kind envisioned under GEI's Oceans theme.

2.2.2 Research Priorities

A number of key research thrusts were identified at the *Future of the Oceans* workshop, which key off and make maximum use of MIT and WHOI's strengths. We summarize here topics that will be of high priority, with the expectation that continued collaboration amongst ocean-oriented faculty and staff will lead to further efforts as the program evolves.

Role of Oceans in Global Climate and Climate Change

In a shared activity with the Climate theme, we propose to capitalize on our longstanding efforts in modeling ocean circulation and biogeochemical cycles and significantly expand our scope to incorporate (i) models of ocean biology (ii) coupling of oceans to the cryosphere and (iii) coupling to the atmosphere above. This will provide a comprehensive tool for the study of the role of the ocean in climate change, for the synthesis and interpretation of in-situ and remote observations of physical, chemical and biological properties of the ocean, and for prototyping new observational systems.

MIT and WHOI have great strengths in observing and modeling the large-scale ocean circulation and biogeochemistry. Moreover we are leaders in developing methods to constrain those models by observations to provide estimates of the evolving state of the ocean. Harnessing MITs great expertise in developing new sensing technologies, algorithms and computation, we propose to use these modeling and observing systems to place constraints on how the oceans and ocean ecosystems have evolved to their present state and how they might evolve in to the future.

Key questions to be addressed include:

- What is the role of the ocean in: the transport of heat and salt around the globe; the carbon cycle; global energy balance and the hydrological cycle; its interaction with the cryosphere; sea-level dynamics?
- What role has the ocean played in large climate changes revealed by the paleo record, such as glacial-interglacial cycles, and what does the record reveal about the stability of the ice sheets and the sensitivity of climate to changing greenhouse gas and orbital forcing?
- What is the likelihood that changes in freshwater forcing, from an altered global hydrological cycle and from increased melt from ice sheets and land glaciers, could lead to drastic shifts in oceanic circulation?
- What components of the ocean circulation are predictable on seasonal to inter-annual to decadal time scales relevant for economic decision making and for climate change mitigation?
- How will CO_2-induced acidification of the ocean alter marine ecosystems and chemistry, how will marine life change and adapt, and how might these changes be mitigated?

The role of oceans in climate is a shared activity between the Oceans theme and the Climate theme. The focus of Climate theme research activity in this thrust area is on the coupling of the atmosphere and the oceans (see Section 2.1.2). The observational and modeling aspects pursued within the Oceans theme link synergistically with that. Significant components of both—those involving life processes—will also be addressed within the Ecological Resilience theme.

Polar Science and Engineering

The interaction of the ocean with the cryosphere is a key component of the global climate system and one that is not very well understood. The Arctic, in particular, is likely to be a very vulnerable part of the climate system, and Arctic ice loss may have major impacts on many other components of the climate. Arctic sea ice has seen a dramatic decline in its seasonal minimum extent over the last three decades, a decline which is more pronounced than predicted by current climate models. Moreover, satellites have documented unexpected and unprecedented accelerations of ice flow and mass loss of the Greenland and Antarctic ice sheets near their marine margins. Processes governing changes in ice sheets have major implications for sea level rise (potential of many meters), which could dwarf other drivers, but remain major unknowns in sea level rise projections. Simple theory suggests that marine-based ice sheets, such as the West Antarctic Ice Sheet (WAIS) with a eustatic sea-level equivalent of 3 to 5 meters, may be inherently unstable.

The polar ocean regions also contain the largest biomass on the planet, and the most productive ecosystems, filled with vast shoals of fish and plankton which provide an important role as food for many species of marine mammal and humanity. The warming of the Arctic has already had a huge impact on the feeding areas and migration routes of many ecologically and economically important fish species, typically increasing the journey to spawning grounds. Some estimates suggest that a reduction of roughly 80% of Antarctic krill population, perhaps the most abundant species on the planet in terms of biomass and a keystone of the Antarctic ecosystem, has occurred over the last 30 years due to reduction in pack ice habitats. Since such changes are occurring extremely rapidly it is essential to make comprehensive observations and develop accurate models to help predict and influence the future of these vital ecosystems.

At the same time, major expansions of resource exploration and extraction activities into the Arctic are being planned. There is thus an urgent need to understand ice mechanics and processes on the scale of engineering applications, in order to design safe systems that will not harm the environment and marine life. Finally, along with the likely thawing of assets in the coming decades, opening of sea routes and increasing access to resources over the pole, and associated sovereignty issues, it is possible that the Arctic may once again become a major concern for national security.

Key questions to be addressed include:

- To what extent does the paleo-record from the last deglaciation provide strong constraints on the potential for future mass loss of polar ice and future sea level rise?
- What is required to develop predictive capabilities of sea level changes and ice sheet mass loss together with reliable uncertainty estimates over the coming decades to centuries?
- To what extent are ocean circulation changes and/or oceanic warming responsible for observed increases in mass discharge from the Greenland and Antarctic ice sheets? Could these processes amplify and trigger catastrophic mass loss or disintegration of

marine ice sheets such as the WAIS, and what are implications for global and regional sea level?

- What is the role of the ocean and sea ice in polar amplification? What might be the local and global consequences of vanishing Arctic sea ice, both on climate and on ecosystems?
- What is the impact of climate change on polar marine ecosystems, which contain most of the world's biomass and supply most of humanity's marine food intake?
- Why are trends in Southern Ocean sea ice cover so radically different from those in the Northern Hemisphere? To which extent are secular trends in the Southern Hemisphere masked by an altered polar vortex as a result of stratospheric ozone depletion, and could this trend be reversed and accelerated with a recovery of the ozone hole?
- Can engineering provide new technologies to measure and monitor critical properties of ice sheets and ice sheet-ocean margins that are currently inaccessible?

This sea ice and polar ocean research elements of this research thrust represent an area of strong synergy with the cryospheric research thrust of the Climate theme, which includes terrestrial snow and ice cover as well as sea ice (see Section 2.1.2).

The Coastal Oceans

The coastal oceans (defined crudely by depths less than about 500 m) are considered separately from the deeper ocean because different processes, such as tides, often dominate and because there of isolation due to of the reluctance for flow on a rotating planet to pass between shallow and deep water. The coastal ocean is extremely diverse, ranging from estuaries and the wave-driven inner shelf to wind-driven and turbulent effects over the continental shelf and slope.

Despite the diversity, there are two common aspects of coastal waters that make them particularly important. One is that, because of physical processes, coastal ocean waters are unusually productive biologically. Thus, most of the world's great fisheries occur in coastal waters, and coastal waters can potentially play a major role in global biogeochemical cycles. Second, coastal waters are more directly affected by human activity than any other part of the ocean. These impacts include habitat modifications, nutrient-laden runoff from land, petroleum exploration and fisheries impacts. Thus, there are compelling scientific and practical reasons to study coastal waters.

The nature of coastal ocean problems drives scientists toward interdisciplinary approaches. Dealing with the important issues often requires a mixture involving physical, biological, chemical, meteorological, glaciological, acoustical and policy-science approaches. This richness makes a range of demands, including the development of sophisticated observational systems that can resolve the required range of variables (plankton species, chemical properties, etc.) over appropriate space and time scales. Further, there is a need for broadly interdisciplinary modeling systems that allow interpretation and forecasting of a range of important properties. From an educational perspective, special problems arise because of the need to maintain excellence in core disciplines, while still providing the breadth that enables meaningful cutting-edge interdisciplinary research.

Key questions that need to be addressed include the following:

- What determines the transport, fate and dispersal of continental runoff waters and the materials and biota carried by them? This is a central question for issues ranging from local eutrophication (“dead zone” generation) to global freshwater cycles
- How do we account for high biological productivity in the ocean? The answer to this is well-known in some settings, but embarrassingly conjectural in many other, important, regions
- How does physical and chemical oceanography impact productive marine ecosystems and the group behavioral dynamics of large oceanic fish shoals, their prey and predators?
- How is the increasing industrialization of coastal oceans affecting marine ecosystems and humanity's dependence on the ocean for food resources?
- What is the role of the coastal ocean in global biogeochemical cycles? The region’s high biological activity would seem to assure that the coastal ocean is a major component in global nutrient and carbon cycles, but there are high degrees of uncertainty about the extent to which materials actually cross the shelf-ocean boundary, and in what form
- How will the coastal oceans respond to and affect global change? Planetary-scale changes in the ocean (acidity, stratification), atmosphere (mean winds and storminess), cryosphere (glacial contraction) and over land (river runoff and dust transport) are all bound to affect the coastal environment in ways that have rarely been treated quantitatively to date
- Turbulent boundary layers fill a much larger portion of the coastal water column than in the deeper ocean. How can we observe, properly quantify, and predict coastal turbulence?

The great overarching issue of coastal oceanography is to understand, quantify and predict exchanges between the coastal zones and the open ocean. The nature of these transports (including mechanisms, spatial distributions and temporal characterization) determine much of the biological and chemical structure of the coastal environment.

Microbial Oceanography

The oceans are dominated by microbial ecosystems. Microscopic organisms represent over 90% of biomass in the oceans, including the majority of the primary photosynthetic producers that form the base of ocean food webs. Yet this property of the oceans has only been appreciated for little more than 30 years, and we still have relatively little understanding of the diversity of microbes and their varied roles in driving biogeochemical processes that ultimately sustain all life in the ocean.

Important efforts in the last few years have focused on unveiling the genetic diversity contained within ocean microbes. The conceptualization of this community as regulated by a “meta-genome" represents a major shift in our approach to environmental biology. Microbial community genome data can be used to predict and verify relevant biotic interactions, functional properties, and biogeochemical capabilities. The basic premises of these efforts are that descriptive biology (at the genomic level) leads to functional prediction, and this in turn leads to the recognition of hidden biotic and biogeochemical interactions within complex systems. These approaches are especially powerful if combined with the study of model organisms to elucidate ecological and evolutionary processes and dynamics. With the advent of new fast and cheap DNA sequencing technology, we are poised for major advances in the coming years, and MIT and WHOI faculty are addressing important areas.

With five faculty members working in marine microbiology and environmental genomics, MIT may have the highest concentration of such expertise in the world. Herein lies a perfect example of how earlier investment by MIT in an area of new research—marine environmental genomics—will yield significant dividends central to developing the Ecological Resilience theme of GEI (Section 2.4).

To fully exploit our new understanding of marine ecosystems requires the development of radical new approaches to biogeochemical modeling. There are several motivating forces for modeling marine ecosystems: (1) Life in the oceans plays a central role in the global carbon cycle, and as such are a key component in climate models. (2) Only through modeling can we begin to understand the self-assembly of microbial-dominated marine ecosystems, and the role they play in cycling of essential elements like N, P, Fe, etc. and (3) Only through modeling can we understand the impact of exploitation of ocean resources on the system. The challenge here is how does one represent the biological complexity necessary in these models while at the same time keeping them computationally feasible?

Key research questions include:

- How do microbial communities self-organize under different physical and chemical regimes in the ocean? What is the minimum number of genes and organisms that can self-organize into a sustainable unit?
- What is the role of predation in driving microbial diversity?
- How do pathogenic bacteria evolve and persist in marine communities? What is the long-term threat to aquaculture and recreational use of the ocean?
- Which genes determine the ecological community in a given environment? How does the meta-genome reflect environmental gradients?
- How can we identify and predict community composition and development from chemical and physical parameters?
- How can we develop ecosystem scale models that reproduce pertinent observed features of the modern oceans and climate system? How can these models be used to explore possible past biogeochemical scenarios and illustrate their large-scale interactions and feedbacks, as recorded in ocean sediments?

Research on marine microbial systems under this research thrust within the Oceans theme represents a major area of synergy with the Ecological Resilience theme—understanding the structure and function of terrestrial and aquatic ecosystems, including marine microbiomes (see Section 2.4.2).

Marine Fisheries

Plankton play a crucial role in ocean ecosystems as a food source for higher organisms such as fish and whales, and also play an important role in biochemical cycles in the ocean including the carbon cycle. Yet evidence suggests that key species, such as Antarctic krill, which in biomass may be the most abundant animal species on the planet, may have suffered population reductions of 80% in the last decades due pack ice melting associated with recent global warming trends.

Fish species are extremely important to the well being of ocean ecosystems and humanity. They provide roughly 40 percent of the protein consumed by nearly two-thirds of the world's population, and are the primary food source for many marine mammals. There is substantial evidence that fish populations are rapidly declining worldwide, yet with conventional sea-going survey methods it is difficult to accurately enumerate fish populations and nearly impossible to study the behavioral dynamics of very large social groups or shoals of fish, including the impacts of population decline. This is because conventional methods rely on highly localized measurements made from slow-moving research vessels, which typically survey along widely spaced line transects to cover the vast areas that fish inhabit, and so greatly under-sample the marine environment in time and space, leaving highly ambiguous records. As a result, the basic group behavioral mechanisms of large fish shoals that govern fundamental processes such as spawning, migration and response to variations in the ocean environment, predators and prey remain largely unknown. Accurate models and forecasts of behavior are not available, making the future of many ecosystems uncertain given current trends in climate change and increasing industrialization of the oceans through expanding human presence. Similar problems exist for studying plankton and marine mammal distributions, behavior, and response to environmental change.

Together, MIT and WHOI have roughly a dozen of the world's leading researchers studying the distributions, behavior and response to environmental change of plankton, fish and marine mammals in the oceans. Also, MIT's expertise in robotics and robotic networks can be tapped to increase knowledge in critical areas of animal group behavior. Key research topics include:

- What are the effects of climate change on oceanic fish, plankton and marine mammal populations, especially in polar ocean regions where change is most dramatic and populations are highest?
- What are the effects of increased human activity on the oceans and their biochemical cycles? What are the effects on marine ecosystems and mammals? Over what time scales will these impacts occur?
- Are there viable methods for restoring decimated marine populations and ecosystems?
- What group behavioral mechanisms govern oceanic fish and plankton shoals? How can they be determined by ocean observations? Are there universal behavioral rules?
- Can numerical models accurately represent and predict fish and plankton shoal behavior, including responses to variations in the physical and chemical ocean environment? How can these models and the underlying theories be tested given the vast scales over which these species range and aggregate?

The challenge is to make the appropriate observations, design accurate models and formulate key policy decisions before deleterious impacts on our ocean fisheries and ecosystems become both too drastic and irreversible.

Integrated Ecological, Chemical and Physical Ocean Sensing using Acoustic Methods

A key element within the Oceans theme will be integration of novel sensing technologies to produce unprecedented observations of coupled biological, chemical and physical processes in the ocean from the macro to the micro scale. These sensing abilities are crucial to scientific, engineering and policy advancements in the ocean environment since they provide the raw data needed to understand, monitor and make predictions about the ocean state. The first looks of newly engineered technology lead to cutting edge scientific discovery and an important cross-fertilization between scientific and technological advances.

Acoustics is a key component of ocean observation at all scales. This is due to the rapid attenuation of optical and electromagnetic waves in water which renders most of the primary remote sensing tools we use in the atmosphere and in space practically useless in the oceans. Acoustic waves, on the other hand, can travel great distances underwater and provide the primary mechanism for remote sensing in the ocean by mankind and many marine creatures. Together MIT and WHOI have arguably the highest concentration of expertise in ocean acoustics in the world, including dozens of the world's leading scientists, engineers and technical staff.

Some key technology development topics include:

- Ocean Acoustic Waveguide Remote Sensing (OAWRS) and local ultrasonics to measure the population distributions and behavior of fish, whales and plankton, their relationships to physical and chemical processes of the ocean and response to human activities and industrialization of the oceans
- Acoustic tagging of marine life to study the behavior of endangered and keystone species of the ocean ecosystem
- Long-range low frequency acoustic thermometry to measure global warming in the oceans
- Acoustic quantification of air-sea mixing and material exchange
- Acoustic measurements of polar pack-ice thickness, glacier and ice-sheet stability
- Underwater acoustic communications and sensing to facilitate human and robot access to and habitation of the marine environment

Ocean Utilization and Engineering

The global ocean constitutes a major center of human activity. It is traversed by increasing number of ships and used for resource exploration and extraction, entertainment and fisheries. Responsible ocean utilization requires novel engineering ideas to preserve the ocean, maintain and enhance the availability of ocean resources, and minimize pollution.

To move toward the goal of responsible ocean utilization, faculty from several MIT engineering departments, the Sloan School of Management, and scientists from WHOI will collaborate on addressing a number of priority research questions related to ships and marine structures—our main access vehicles and man-made stations at sea. Many of them also apply to

Autonomous Vehicles (AUVs) and buoys that are important platforms for deploying environmental monitoring sensors. Key research questions include:

- What new nano-structured coatings and surface treatments can be introduced to protect ships, as well as environmental monitoring buoys from corrosion, bio-fouling and deposits?
- What new designs and autonomous deployment and distributed control can be introduced to make Autonomous Underwater Vehicles (AUVs) capable of wide-spread and effective ocean mapping, environmental sensing, reconnaissance and exploration?
- What real-time coupled radar-satellite sea monitoring capabilities will allow for the prediction of ship motions and identify the occurrence, location and height of extreme, "rogue" waves?
- How can arrays of inexpensive, robust and low-power pressure and velocity micro-sensors be used to detect the environment around a vessel or AUV and monitor and control phenomena that affect navigation?

2.2.3 Organization and Development

Major participants in GEI's Oceans theme will include the departments of Earth, Atmospheric and Planetary Sciences (primarily through the Program in Atmospheres, Oceans and Climate), Civil and Environmental Engineering (primarily through the Parsons Lab), and Mechanical Engineering (primarily through the Center for Ocean Engineering), as well as WHOI. Other participating organizations will include the Sea Grant College Program, the MIT Energy Initiative, and other academic departments such as Biology, as appropriate.

While research and education activities within GEI's Oceans theme will launch with the significant momentum and resources of these participating organizations, additional resources will be needed to realize their full potential. Necessary support for new programs common to all GEI themes includes: graduate and post-doctoral fellowships, undergraduate research opportunities, ignition grants, visiting faculty, essential facilitative administrative support, and targeted community-building and outreach activities. Activities within GEI's Oceans theme also need special support to:

- Hold an annual joint meeting of affiliated MIT faculty and WHOI researchers, which will enhance the collaborative strength of the MIT-WHOI alliance
- Pursue oceanographic field experiments to jump-start the use of new sensing technologies for monitoring the impact of climate change and increased human activity on highly vulnerable marine ecosystems around the world

Finally, faculty development in certain priority areas of research expertise would also enhance the ability of activities within GEI's Oceans theme to reach their full potential. These areas include:

- *Ocean Sensing Technology and Engineering*—innovative ocean sensing technologies to observe and quantify geophysical, chemical and biological processes in the oceans. These technologies would include acoustic, electromagnetic, mechanical and chemical methods, with an emphasis on wide-area synoptic approaches that can help quantify the impacts of climate change and increased human activity on ocean ecosystems. This research area particularly complements that of ocean ecology (described immediately below), and that of Chemical Sensors and Instrumentation under the Ecological Resilience theme (Section 2.4.3)

- *Ocean Ecology*—investigation of higher trophic levels using innovative sensing technologies. Changes to marine ecosystems are occurring rapidly over vast areas, but sensing capabilities are also advancing. This priority research area would help coalesce the diverse efforts of several research groups at MIT and amplify efforts to observe, understand and model marine ecosystems, forecast trends and inform policy decisions. This same research area is a priority for the Ecological Resilience theme (Section 2.4.3)
- *Marine Biogeochemistry*—observing and modeling ocean biogeochemical cycles, which determine how chemical elements move through both the biotic and abiotic components of the ocean ecosystem to regulate the chemical environment that supports all marine life. This research area particularly complements priorities within the Climate and Ecological Resilience themes, and would foster collaboration between physical, chemical and biological oceanographers at MIT, while also broadening the educational experience and research opportunities offered through the MIT/WHOI Joint Program

2.3 Water

By most estimates, global population will grow from nearly 7 billion people today to more than nine billion by 2050. Virtually all of these additional people will live in the developing world; most will reside in cities. Every one of them will need daily access to fresh water—a basic necessity already difficult to obtain. One billion people already lack a reliable water supply, while two billion are without adequate sanitation. Shortages plague even wealthy nations, including the United States. The stress shows in our global systems and supplies of energy, healthcare, and food—and the projected effects of global climate change will only compound these problems.

Ensuring fresh water for all is an urgent, fundamental challenge for the 21st Century. Water issues, however, are tangled knots of technical hurdles, regional considerations, economic factors, and matters related to policy and governance. Unraveling the challenge of water, therefore, requires a broad-based approach to innovation and deployment that encompasses analysis and modeling, engineering, basic science, systems design, and policy programs—all aspects of MIT's unique strength. It is imperative that the Institute and its research community focus attention on problem-solving in this fundamental challenge facing human societies and human welfare.

2.3.1 Opportunity at MIT

The Institute already wrestles with water issues in many departments, laboratories, classes and projects. MIT faculty, students and staff today offer substantial expertise in:

- Forecasting and responding to the likely impacts of global climate change on water supply in both coastal and inland regions

- Developing advanced and economical technologies for water purification, seawater desalination, and waste-water recycling
- Developing and disseminating water purification and distribution technology for the developing world, especially regions that are impoverished or off the grid
- Developing and disseminating strategies for urban design that conserve water and facilitate its distribution for rising megacities, water-starved Middle Eastern and North African countries, or the post-industrial world
- Analysis of national and international policies that drive water supply, pricing, and conservation, such as inefficient use of water in post-industrial societies or the failure to assure clean water supplies in developing countries located in "water rich" regions
- The fundamental science of hydrology including flow in rivers and lakes, porous media flow through soils and aquifers, the coupled processes of water and energy exchange between the atmosphere and land surface

Indeed historically MIT has played a significant role in shaping the engineering and scientific disciplines that deal with water. Remarkably some of the transformational scientific and technological advances in water research have emerged out of MIT.

MIT was a leader in the development of modern sanitation engineering, including the pioneering work of Ellen Swallow Richards. Scientific hydrology emerged out of MIT with the trailblazing contributions of Emeritus Professor Peter S. Eagleson. Significant developments in integrating advances in aquatic chemistry and microbiology into water and environmental science also can trace many of their origins to MIT and the Ralph M. Parsons Laboratory. The Institute is ready and poised to take on even more challenging in developing the engineering and scientific bases for dealing with this essential substance for human society.

While the current depth and range of institutional capacity in water at MIT is impressive, most of the projects and programs have proceeded independently. Bringing water to the forefront of cross-disciplinary research challenges at the Institute will engage new ideas and new technologies from the immense MIT portfolio in order to develop impactful solutions. The Institute is positioned to take on a leadership role as a source of innovate solutions to this long-standing and still daunting problem.

As a first step in harnessing the separate efforts together and share their united strength with the broader MIT community the ERC sponsored Institute-wide symposium *Rethinking Water: A Critical Resource* (http://web.mit.edu/water) on May 20, 2010. More than 300 members of the MIT community attended this day-long workshop. The audience included MIT faculty, students and alumni, as well as venture capitalists from the area, and industrial and research leaders from around the world. The intensity of community interest surrounding clean water technologies was impressive.

Activities within GEI's Water theme will comprise an integrated research and educational community spanning the engineering, scientific and social aspects of water. This enterprise will facilitate research, foster education, and engage the MIT community on the pressing challenges of global water problems.

2.3.2 Research Priorities

The problem of fresh water availability spans scales from global to local where its impacts on human welfare are manifested. There are also scientific, technological, cultural, and political dimensions associated with it. A major outcome of the *Rethinking Water* workshop was the identification of three areas of priority research where MIT is poised to make major contributions:

- Water in a Changing Global Environment
- Clean Water Technologies
- Design for Water, Landscape and Social Change

Taken together, these three major research thrusts span the physical, technological and social dimensions to the water challenge. They are designed to bring together faculty and expertise from all five schools at MIT and engage them in creative and collaborative problem-solving.

These thrusts have also been vetted through a year of sustained conversation amongst faculty across the Institute, the Environmental Research Council's call for concept papers in June 2010, and discussions convened by the Associate Provost for International Programs. Each thrust area also encompasses strong educational and service components. The specific research activities will change over time as the challenges and opportunities evolve and more diverse talent from the MIT community is drawn in. Nevertheless GEI will launch with a Water theme organized around this initial set of research thrusts and associated priority activities under each.

The first research thrust represents an area of synergy with both the Climate theme under its *Water and Climate* thrust (see Section 2.1.2), and the Oceans theme under its *Role of Oceans in Global Climate and Climate Change* thrust (see Section 2.2.2). The third topic—Design for Water, Landscape and Social Change—represents an area of strong synergy across several research thrusts and priorities within the Sustainable Societies theme (see Section 2.6.2). Together, these three inaugural research thrusts of GEI's Water theme will form the foundation of MIT's renewed commitment to bring transformational research to this grand challenge facing society and human welfare.

Water in a Changing Global Environment

The patterns of evaporation and precipitation that set the availability of freshwater on land are shaped by the circulations of the atmosphere and oceans. Small changes in these circulations as a result of climate change or climate variability will result in dramatic shifts in the water cycle. Hence understanding and forecasting climate change is of crucial importance to assess the future supplies of freshwater for drinking, food and energy production. Many faculty members at MIT study the Earth's climate, its changes and its impact on the water cycle. These activities, however, are presently not linked to research on adaptation and mitigation to changes in water resources, nor to research in water technology. Should these activities be linked, MIT could move to the forefront in tackling the question of how to respond to water needs in this century.

The existing stocks and supplies of freshwater are also under stress due to the accumulation of chemicals that are harmful to the living communities that depend on the water availability. For example the inorganic nitrogen fertilizers that made the Green Revolution and the several-fold increase in agricultural productivity possible also cause biological blooms in water bodies that receive runoff from land. Harmful algal blooms now pose a significant threat to the health and productivity of many coastal and inland water body systems. Chemicals that are synthesized or mobilized from the environment in unusual amounts are also prevalent threats to the availability of safe freshwater. These compounds are often not part of any major global biogeochemical cycle and therefore do not breakdown as part of these cycles. The prediction of the impact of chemical accumulations in freshwater systems, coastal water bodies and the open ocean requires leaps in the sensitivity of chemical sensing and transport modeling in the environment as well as fundamental new understanding of how microbes, photo-chemical processes, and chemical oxidation mobilize, transform and change chemical compounds in the environment.

The MIT research community has significant capability to engage in these scientific and technological challenges. The goal is to create a rational proactive—rather than reactive—approach to managing the chemistry and quality of freshwater in the environment that is fundamental to assessing its availability for living beings including humans. Particular areas of active and anticipated research include:

- *Climate change and the water cycle*—MIT is at the forefront in studying the impact of climate change on the water cycle and precipitation extremes, hurricane intensity, reshaping landscapes, the cryosphere, the water cycle and hydroclimate variability. Exciting new research also shows the important role the oceans play in shaping the water cycle (incubated within GEI's Climate and Oceans themes)
- *Predicting regional changes in water cycle*—Global climate models have little skill in predicting regional changes of precipitation and evaporation. There is growing evidence that the skill increases substantially if one couples an atmospheric model with an ocean model initialized with the observed mean state. This line of research could lead to decadal predictions of devastating regional climate patterns like droughts
- *Monitoring the water cycle*—Our skill in forecasting changes in the water cycle is still limited. It is therefore necessary to monitor the water cycle to monitor ongoing changes and to provide ground truth for forecast models. MIT faculty are engaged in developing new technologies to monitor the water cycle from space
- *Geo-engineering and the water cycle*—Geoengineering focuses on mitigating the radiative effects of carbon dioxide on mean temperatures. The impacts on the water cycle received little attention, but might be the real issue for mankind
- *Water contamination*—Anthropogenic impacts on the chemical composition of groundwater, rivers, lakes, and estuaries are significant in many places; research into the changing composition of these waters and the mechanisms causing the changes would contribute to our ability to use water resources
- *Finding freshwater reservoirs*—Subsurface aquifers are a major source of freshwater especially when seasonal surface river and lake water supplies are limited. These water reservoirs exist within complex and often deep hydrogeologic structures. The geophysical methods for probing into these systems and the development of models that can predict flow and transport in porous media are fundamental to managing the subsurface aquifers

Clean Water Technologies

Regional water scarcity has diverse causes, including poverty, lack of adequate infrastructure, overpopulation, overconsumption, biological and chemical contamination, and simply arid climates. Correspondingly, the appropriate technologies for supplying clean water vary widely from region to region depending on the social and physiographical context. In many cases, water shortage results from a lack of potable water, rather than a lack of water per se, as for example in some urban centers near the ocean. In these situations, technology for purifying or desalinating water is essential. In other situations, water supply from any source is very limited, so that technologies for water recycling and conservation are needed. Recycling of wastewater has been implemented in Singapore, Orange County, Western Australia, and water scarce areas. In still other cases, a lack of distribution or storage of potable water can be limiting. Indeed, 20% to 30% of the water put into a typical urban pipeline is lost to leakage, and outright piracy is a significant problem in 3rd world megacities. Lack of storage infrastructure limits dry season water supply in some monsoon climates.

Research in clean water technology at MIT spans most departments in the School of Engineering, particularly the Mechanical, Chemical, Civil and Environmental, and Materials Science and Engineering departments, as well as some parts of the School of Science. The sponsors of this research are quite diverse, but they include a number of large-scale international partnerships, such as the King Fahd University of Petroleum and Minerals, Singapore-MIT Alliance for Research and Technology, and Masdar programs. Examples of current MIT research in clean water technology include:

- *Advanced membranes*—encompassing layer-by-layer processes, fiber spinning, iCVD, ceramic/zeolite technologies, and mechanical characterization and design
- *Nanotechnology and advanced materials*—including nanoporous membranes, monodisperse ceramic filters, and coating resistance to saline water scale deposition
- *Electrochemical and physicochemical technologies*—including modulated transport through carbon nanotubes, electro-osmotic techniques, monolithically integrated ion depletion channels, and nanofibrous capacitive deionization channels
- *Leak detection technologies*—including RFID systems, in-pipe robotics, and acoustic systems, together with advanced signal process methods. These include both lab and field-deployed research
- *Advanced sensors and control* —water production systems require highly optimized performance to produce water at a reasonable cost. Advanced control algorithms, sensors, and actuators are essential to overall performance
- *Developing world water purification systems*—targeted specifically toward accessible technologies that can be locally implemented and deployed

Design for Water, Landscape and Social Change

Throughout history, water resources have served as a vital instrument of social change, including changes in the built environment from the scale of buildings to landscapes, metropolitan regions and complex river basins. MIT has strengths at each scale and GEI's Water theme, in concert with its Sustainable Societies theme, will concentrate in four priority areas that will help reshape our understanding of the landscapes of water and redefine MIT's contribution to the field. These four priority areas include:

- *Water, Sanitation, Water Quality and Environmental Management*—this field complements the area of Clean Water Technologies. It encompasses legal research on human rights to water and sanitation; D-Lab studies of low-cost water and sanitation systems; Poverty-lab randomized trials of policy interventions; Sloan water innovation and entrepreneurship; and water in environmental economics
- *Water-Conserving Landscape and Urban Design*—MIT is advancing the field of water-conserving design, which links progressive approaches to storm-water flooding with historical and cross-cultural perspectives on water development, and high water use efficiency systems in the U.S., Europe, South Asia, and Middle East
- *Water in Regional Ecological Restoration and Resilience*—MIT research on restoring aquatic systems ranges from physical modeling in the Parsons Lab to regional and global policy experiments
- *Water in Transboundary and Global Environmental Policy Design*—this field bridges MIT's strengths in water resources and global change. It includes transboundary negotiation and policy design, and water resources adaptation to climate change

2.3.3 Organization and Development

The Water theme of GEI encompasses a collaborative, organizing umbrella for the many relevant research activities on water already occurring at MIT in the departments of Civil and Environmental Engineering; Mechanical Engineering; Chemical Engineering; Materials Science and Engineering; Earth, Atmospheric and Planetary Sciences; Urban Studies and Planning; and History, as well as the Sloan School of Management. The Water theme also represents an area of important collaborative interaction with MITEI on issues of water and energy, and with WHOI on issues of coastal science and urbanization. Finally, insofar as issues of water are of central importance to each of GEI's other inaugural research themes, internal coordination of research efforts will be vital.

Research and education activities within GEI's Water theme will launch with the following primary goals:

- Building community across the broadest spectrum of water related research at MIT and coordinating activities across the three primary themes for priority research
- Developing problem-oriented educational program, including survey level courses for graduate students and an eventual undergraduate minor
- Promoting the MIT Campus as a living laboratory for engaging students in the real-world challenges of managing all aspects of water cycle, consumption and infrastructure
- Establishing innovation competitions for developing clean water systems
- Sponsoring field trips to examine real-world challenges beyond MIT and identify high-impact issues not adequately addressed by our current research portfolio and curriculum

- Leveraging student outreach and service opportunities through established MIT programs such as Civil and Environmental Engineering's SM degree and D-Lab
- Creating community engagement through sponsored colloquia, teach-ins and other outreach events both within and beyond MIT

While the activities within GEI's Water theme will launch with the significant momentum and resources of the participating faculty and departments, additional resources will be needed to realize their full potential. Necessary support for new programs common to all GEI themes includes: graduate and post-doctoral fellowships, undergraduate research opportunities, ignition grants, visiting faculty, essential facilitative administrative support, and targeted community-building and outreach activities. Special support is also needed to establish, maintain and staff a state-of-the-art water chemistry lab, which will provide a key research support and student training resource currently lacking at MIT.

Finally, faculty development in certain priority areas of research expertise would also enhance the ability of activities within GEI's Water theme to reach their full potential. These areas include:

- *Clean Water Technology*—focused on water purification, this research area encompasses specialties such as: advanced membranes for water separation, reverse osmosis and bioreactors; nanotechnology and advanced materials for filtration, coatings for scale control in desalination systems and catalytic water purification systems; electrochemical and physiochemical technologies including fundamental and applied research in techniques for the removal of ions, colloids, and biological contaminates; and advanced sensors and controls for leak detection, optimized power management for photovoltaic-driven purification systems, and control of hybrid water/power coproduction systems
- *Terrestrial Ecology*—this area of expertise is critical to all water, climate and ecosystems research within GEI. The most important new work in hydrology is very closely related to ecology. Ecosystems control water flows. Transpiration by plants is the largest flux from the terrestrial hydrologic system and plants control the processes by which precipitation infiltrates soils, influencing the development of soils and large-scale drainage systems. Likewise, water flow controls ecosystem function and biogeochemical cycles. MIT already has an excellent hydrology faculty. The addition of terrestrial ecology would greatly strengthen the Institute
- *Water, Urbanism and Political Economy*—links water-conserving urban design with water resources policy. Conventionally, this intersection is addressed by consortia of scholars who have emerged from established disciplines and professions, e.g. economics, political science, urban planning, and landscape architecture. Given other new programs in urbanism (School of Architecture and Planning) and sustainability (Sloan), expertise in this area would help establish trans-disciplinary leadership in the field of "Water and Society" in rapidly urbanizing regions of the world
- *Professors of Practice*—Professors-of-Practice would bring the expert perspectives of real-world water managers to MIT's research and education portfolio on water, particularly in terms of the practical aspects of water supply and treatment in the developing world not typically well represented within academia

2.4 Ecological Resilience

The forces of natural selection and evolution have shaped life on Earth, which in turn determines the composition of our planet's soil, air and water. Human activities are now among the strongest agents of natural selection on Earth—changing the trajectory of ecosystems and the habitats they sustain, and even global evolution in ways both unintended and as yet unimagined.

Over the last 200 years, humans have transformed both terrestrial and aquatic ecosystems at the global scale, altering the global biogeochemical cycles of compounds that affect living systems and climate. A sizeable fraction of Earth's primary productivity—the production of the organic matter upon which all life depends—has been co-opted by humans, fundamentally changing the structure of Earth's ecosystems and the diversity of life that sustains them. Modern agriculture is so heavily mechanized and dependent on synthetic fertilizers that each food calorie we consume requires several calories of fossil fuel. At the same time we are harvesting many natural resources at unsustainable rates, testing and with ecologically damaging consequences. For example, over half of all accessible fresh water is on Earth is now diverted for human needs, often with little or no thought for the broader environmental impacts. These actions test the limits of ecosystem resilience and putting in jeopardy the services they provide.

Our biosphere today represents the co-evolution of life and Earth over 3.5 billion years, with billions of years yet to come. Along the way, energy from the sun has combined with essential chemical elements to create a vast array of life arranged in complex ecosystems with highly efficient resource recycling and waste minimization. Our challenge is to learn the principles governing how these living systems function, for in their design lies the blueprint for sustainable human societies.

To succeed in this effort will require a unique collaboration of the physical, chemical and life sciences coupled with engineering and cutting edge technologies. MIT is uniquely suited to lead this challenge. Through this collaborative alliance we will bring the power of modern biology and engineering to ecology, thereby creating a new discipline—Modern Ecology[2].

2.4.1 Opportunity at MIT

Ecology is to environmental science as physics is to engineering. It is the foundation discipline—the study of the structure and function of ecosystems—that organizes our knowledge into a framework useful for applications. A strong research program and a tiered curriculum in ecology are absolutely essential to the vitality of GEI. At the moment, MIT is one of the few top-tier universities with no coherent program in ecology, ecosystems or evolutionary biology. Within this apparent shortcoming, however, lies a unique opportunity—to invent the new discipline of Modern Ecology as a unique MIT brand.

Fortunately, MIT does already have robust research programs in modern biology and many of the areas vital to understanding the complex physical, chemical and biological components of the ecosystems. Augmenting these strengths in science and engineering with strategic additions of expertise in key areas of ecology—e.g. terrestrial ecology, theoretical

[2] Science-based approaches to human health launched "Modern Medicine. The discovery of DNA and the genetic code launched the field of molecular biology from which "Modern Biology" emerged. Taking our cues from these powerful transformations, we call this new discipline "Modern Ecology".

ecology and ecosystem dynamics—will enable MIT to build the flagship program in Modern Ecology from the ground up. No other institution offers the same critical combination of existing strength and wide-open opportunity to innovate in this vital area.

We are particularly strong in microbial ecological genomics, which, coupled with the current momentum of the Human Microbiome project, provides an unprecedented opportunity for convergence between the biomedical and environmental sciences at MIT. Creating and developing the Ecological Resilience theme within GEI is something that MIT can and must do as a legacy to the future.

2.4.2 Research Priorities

MIT's existing strengths in aquatic ecosystems—in particular microbiology and genomics—complement priority research thrusts within the Climate and Oceans themes: *Co-evolution of Life and Climate over Earth History* and *Biogeochemical Cycles and Climate* (see Section 2.1.2); and *Microbial Oceanography* (see Section 2.2.2). Other priority research thrusts critical to the creation of Modern Ecology at MIT include:

- Biological Diversity and Biogeochemical Function in Ecosystems
- Ecosystem Genomics
- Theoretical Ecology
- Sensors for Environmental Biogeochemistry
- Modeling Terrestrial and Marine Ecosystem Dynamics

Modern Ecology emerges from a unique collaborative alliance between the physical and life sciences with engineering. It has its underpinnings in genomics, because it is within the genomes of organisms that the information governing ecosystem design lays. It is enabled by advances in theoretical ecology, through which we can begin to understand how this information scales up to determine the properties of organisms, populations, communities, ecosystems, and ultimately the biosphere. It is also enabled by advanced sensor technologies, which can create data streams to aid in predicting the trajectories of ecosystem properties and the human services they provide. Finally, through the development of sophisticated models we will be able to combine theory with data to generate future scenarios to guide environmental decision making.

We envision a near future when research within GEI's Ecological Resilience theme will link with exciting new enterprises in biomedical research also being pioneered at MIT, such as the Human Microbiome Project. This will enable truly innovative contributions to the life sciences, and human and ecosystem health. In fact, there is growing recognition that the human body is itself an ecosystem—the natural habitat of thousands of species of beneficial microbes that carry out essential functions to maintain our health. The assembly rules that govern our personal ecosystems are the same as those that govern all ecosystems—in soil, water and air, and from microbial to mega-scale. To understand these inherent rules of ecosystem assembly is the goal of Modern Ecology, for in them lies a critical key to designing sustainable practices for living on Earth.

Biological Diversity and Biogeochemical Function in Ecosystems

The services provided by ecosystems, such as food, fiber, and air and water purification, are dependent on the types of organisms that comprise them. For example ocean microbes provide all the organic matter, through photosynthesis, that forms the base of the food webs that yield the fish that feed humans. Yet we do not fully know how the diversity of organisms comprising food webs influences the flow of energy and matter through them—i.e. their biogeochemistry. Understanding this link between the structure and function of ecosystems is a major challenge of Modern Ecology.

Our starting point based on current efforts at MIT is focused on marine microbes since these represent key drivers in globally important biogeochemical cycles. The ocean is fundamentally a microbial ecosystem with over 90% of its biomass contained in microscopic organisms. The information in the genomes of a liter of these microbes is equal to that in the entire human genome. This information can be used to infer key biogeochemical processes, including the production and consumption of greenhouse gases, and important links in global cycles of essential elements like nitrogen, sulfur and phosphorous.

This research thrust of the Ecological Resilience theme is incubated in the Oceans theme as microbial oceanography. But it is here that it is fully developed into a major tenet of Modern Ecology—inferring biogeochemical function in ecosystems from the genetic composition. This is made possible by advanced genomic sequencing technologies and key theoretical developments in interpreting the genetic and biogeochemical data. Key research questions to be addressed include:

- To what extent do ecological communities assemble according to specific and thus predictable rules? How do these rules relate to biogeochemical function in ecosystems?
- How do assemblages and networks in communities affect the flow of energy and matter through them?
- What are the networks of interactions that provide stability to communities?
- How does biodiversity in ecosystems make them resilient towards natural and anthropogenic disturbances?

Ecosystem Genomics

No one organism contains all the genes necessary to perform the diverse biogeochemical reactions driving elemental cycles in the biosphere, yet distributed amongst the organisms are all the functions necessary to define the interaction of the community with its environment. Much as it is necessary to understand the components of the human body at all scales—from genes to organs to systems—to make advances in human health, we need to understand the components of ecosystems at all scales to develop predictive capabilities. This emerging concept of the 'ecosystem genome', illuminated through metagenomics, allows us to pose many exciting new fundamental questions:

- How many genes with unique functions are there in an ecosystem and how are they distributed among organisms?

- Are there a well-defined families of genes associated with ecological communities in different environments?
- How does the ecological genome change along environmental gradients?
- What is the minimum number of genes and organisms that can self-organize into a sustainable biome or ecosystem?

Theoretical Ecology

The Earth's ecosystems form challenging complex systems and their spatial organization and temporal dynamics are often remarkable puzzles. Ecosystems often "self-organize" into quasi-equilibrium states that are fairly robust and resistant to change. But the systems can exist in and jump between many different quasi-equilibrium states, as evidenced by the dramatic changes on Earth over the course of evolution. Recent developments in complexity theory and computation can be applied to this system problem—the ultimate complex system problems—in ways that will help us understand how detailed interactions at the microscale result in emergent properties at the macroscale. This is but one of the major challenges in Modern Ecology. Others include:

- Why do many phenomena in living systems obey scaling laws?
- What dictates the elemental stoichiometry of living systems, and how is it influenced by the genetic code and vice versa?
- What is the relationship between habitat patchiness and species diversity?
- What is the optimal design of nature reserves for sustaining the maximum diversity of species?
- What are the characteristics of introduced species that determine whether they will become invasive pests?

Sensors for Environmental Biogeochemistry

Nutrients and biogeochemicals are the life-blood of ecosystems. Diverse ecosystems also work together to form the global cycling of these substances. Key to Modern Ecology is the introduction of new instrumentation to detect even trace amounts of nutrients and biogeochemicals.

A revolution in environmental sensing is on the horizon, and it is one MIT can and should lead. Data from networks of micro-scale chemical and biological sensors promise exciting new avenues for environmental research, and could soon become ubiquitous. With appropriate research and development, we might, for example, be able to sample air composition as we walk, drive, or fly. We should be able to seed an ecosystem with thousands of cheap sensors that will tell us about the subsequent chemistry and the physics of processes in the environment. The methods of modern biological engineering could permit us to create microorganisms that can sense the "health" of natural ecosystems. Globally distributed sensors sending their data to satellites could augment remote sensing to help provide the "whole-Earth" picture.

Developing a set of new physical, chemical and biological sensing and data collection capabilities will be a critical enabler to Modern Ecology and our understanding of ecosystems.

We envision teams of scientists and engineers working together to define the environmental and ecological measurements needed and devise the technologies to acquire them. With its broad expertise in the natural sciences, chemical, mechanical and electrical engineering, and computer science, materials science, and sensor optics, MIT has a unique opportunity to lead the world in developing the next generation of sensors, such as:

- Sensors to measure nitrate and ammonium, which are key controls on the biological productivity of many ecosystems, both marine and terrestrial
- Sensors to measure phosphorous species, which often control the productivity of fresh waters
- Sensors for methane, carbon dioxide, and other metabolic gases, many of whose sources are not well quantified, and whose activities affect both biology and climate
- Sensors for toxic chemicals, including various species of metals such as arsenic, lead, and mercury, as well as toxic organic compounds
- Sensors for major ions, whose composition is broadly diagnostic of water source and geochemical history

Modeling Terrestrial and Marine Ecosystem Dynamics

Mathematical models of ecosystem dynamics connect and reconcile experimental and observational data on both terrestrial and marine ecosystems. These models cut across enormous ranges of scale in space and time. Further challenges are that they need to capture interactions among organisms and interactions between the biotic and abiotic environments. Approaches to ecosystem modeling are in their infancy, and greatly in need of inspired improvements—some of which are already being pioneered at MIT. These models are essential for exploring potential outcomes of human and natural interventions in ecosystems and biogeochemical cycles.

Key research questions to be addressed include:

- How do we develop the capability to predict community composition, function, and development based on genomic information and chemical and physical parameters?
- What are the critical feedback loops between the biotic and abiotic components of microbial and terrestrial vegetation ecosystems as they co-evolve?
- What are past biochemical scenarios and their large-scale interactions and feedbacks, which are recorded in sediments?
- How can we best combine data from sensors and observation systems with modeling to enhance our predictive powers of terrestrial and marine ecosystem change?

2.4.3 Organization and Development

In addition to providing research momentum to GEI as a whole, the Earth System Initiative (ESI) lends a particularly strong intellectual foundation to the Initiative's Ecological Resilience theme. But while research and education activities within this theme will launch with significant momentum and resources, additional support will be needed to realize their full potential. Necessary support for new programs common to all GEI themes includes: graduate and post-doctoral fellowships, undergraduate research opportunities, ignition grants, visiting faculty, essential facilitative administrative support, and targeted community-building and outreach activities.

Finally, faculty development in certain priority areas of research expertise would also enhance the ability of activities within GEI's Ecological Resilience theme to reach their full potential. These areas include:

- *Theoretical Ecology*—addresses the pressing need to develop both a fundamental and a mathematical understanding of the collective macroscopic behavior of ecosystems subject to ongoing evolution. Developed slowly over the past century by applied mathematicians who recognized the importance of understanding Nature's patterns for the purposes of conservation and designing sustainable human societies, theoretical ecology is now a wide open emerging field in which MIT can and should establish its leadership
- *Terrestrial Ecology*—providing a bridge of understanding between microbial ecosystems and biogeochemical cycles, among other contributions, this area of expertise would be a critical enabler for both the Ecological Resilience and Water themes. Potential areas of contribution include how microbial processes influence greenhouse gas production and consumption in soils, how to maximize agricultural production with minimal input of fertilizer, and the resilience of terrestrial ecosystems to environmental change
- *Biogeochemical Sensors and Instrumentation*—this area of expertise addresses the critical need to develop sensors for ecosystem and environmental parameters that are sufficiently small, simple and inexpensive to be deployed in large numbers or onboard autonomous vehicles for maximum spatial and temporal data acquisition. The development and deployment of such sensors represents an emerging field in environmental science—one that MIT is well-poised to lead

2.5 Contamination Mitigation

Over the past century, the use of both synthetic and naturally occurring chemicals, pharmaceuticals and materials—and more recently genetically modified organisms—has grown to become an integral part of modern industrial society. Without doubt, use of these substances and organisms has fueled innovation and enhanced productivity in industrial and electronics manufacturing, drug design, food production and many other essential sectors. But it has also created a well-documented history of contaminant exposure resulting in profound damage to both ecosystems and human health.

Some of these exposure events have been intentional such as spraying with DDT (dichlorodiphenyltrichloroethane)—an insecticide introduced in the 1940s, produced in quantity and widely used around the globe. Insecticides can benefit mankind by reducing the populations of disease carrying insects and by protecting crops. However, DDT was banned in the US in 1972 following the discovery of its adverse ecosystem and health effects. But many other exposures have been unintentional such as those to MTBE (methyl tertiary butyl ether)—an additive in gasoline introduced with the goal of reducing air pollution. MTBE additive to gasoline satisfied this technical need and could be synthesized economically from available feed stocks. As a result, companies invested billions of dollars in setting up the infrastructure to supply this new gasoline additive in large quantities. But later when MTBE exposure was found to lead to groundwater contamination, industry was forced to abandon billions of dollars in R&D and infrastructure investment.

As these examples illustrate, our approach to deploying new substances generally follows a 'trial-and-error' scenario. A new substance is introduced and only after long periods of exposure and the appearance of human disease or ecosystem damage do industry, government and public attention turn to controlling its use and release. This cycle of introducing new substances—in particular synthesized chemicals, materials and now organisms—with great promise, widespread development and use, and later removal from production after the discovery of exposure risks is both all too common, and all too costly.

Clearly this model for doing business should be transformed. It can be too late (or extremely expensive) to address environmental damages after they have occurred. The challenge is to create the knowledge base for a new mode of operation based on scientific and technological efforts to evaluate and even design new substances before they are put into large-scale use—the benign-by-design approach. Here we attack the problem at the "research stage." Environmental impact and human toxicological assessments are all made while new substances are still being developed. Indeed, environmental, workplace and public health risks should be used, along with technical and cost considerations, in the choice of acceptable synthetic pathway options. This benign-by-design approach will become increasingly important as the creation and use of synthetic chemicals, materials and organisms flourishes in everything from batteries to tennis rackets to corn seed. Gains in efficiency and performance should not carry unforeseen future costs in terms of damage to human health and environmental quality.

Also essential to the benign-by-design approach is the redesign of current chemical processes for efficiency, including the use of micro-reactor technology, and the redesign of processes to replace current manufacturing methods with green chemistry approaches. Redesigning chemical processes so that they are efficient and environmentally benign requires fundamental chemistry, as well as contributions from chemical and biological engineering. The creation of new greener methods for synthesis of materials necessitates innovation on the part of chemists and biochemists.

A new benign-by-design model will emerge out of the integration of fundamental chemistry and biology with technology and engineering design, and the basic principles of innovation and business. The goal is to produce the knowledge base needed to guide the production of useful synthetic compounds, materials and organisms that support sustainable economic growth and maintain human and health and ecosystem quality.

At the same time, chemists, biologists, toxicologists, social scientists and engineers must continue to address existing and unavoidable future environmental contamination problems. Despite our best efforts and intentions, human activities will always produce contamination issues requiring remediation. We will continue to need novel methods to clean up our cities, our water, our atmosphere and our rural communities. Here, we can draw on expertise from the other research themes of GEI, and reach out to MIT laboratories already working in this area.

Development of a technology-based management approach is closely allied to the issue of environmentally sounder and inherently safer design, but the former extends beyond design to encompass decision-making within firms and regulatory agencies. The technology-based management approach is centered encouraging chemical producers and users to conduct alternative and technology option analyses to identify opportunities for design or redesign. MIT has not only the technological literacy to extend the design-for-the-environment paradigm to industrial and governmental decision-making frameworks, but also the extensive public policy expertise in political science, urban studies, and technology and law to affect the basis and heuristics used in the decision-making process.

2.5.1 Opportunity at MIT

The design or redesign of chemical processes, materials and bio-engineered organisms that minimize environmental and human health risks pose both scientific and management challenges. Organized through GEI's Contamination Mitigation theme, MIT possesses the scientific, industrial, and public policy expertise to address these challenges in a unique, integrated, and coherent way. Its research and teaching activities in basic sciences, toxicology, chemical engineering, materials science, product development, industrial design, and policy, law and economics place it as a pre-eminent institution to contribute to a new era in the advancement of sustainable industry, environmental quality and public health.

Perhaps more importantly, MIT is the site of research on many new chemicals, materials and processes. And appraisal of environmental and human health effects needs to be pursued at the research stage, not after products and processes have reached the market. Hence, we are ideally suited to evaluate new product/process design in both economic terms (e.g., material and energy use) and environmental terms (e.g., exposure and toxicity assessments) at an early stage to optimize "green" development.

MIT has considerable expertise in the evaluation of the biological effects of exposure to environmental agents. The MIT Center for Environmental Health Sciences (CEHS) is a flagship organization in this research area, drawing on faculty in the departments of Biological Engineering, Biology, Chemistry as well as others. New designs of chemical, materials, and bioengineered organisms are topics of study in most departments in schools of Science and Engineering. There is incredible talent and innovation in these areas at the Institute. Yet they are fragmented and research is mostly conducted independently. The goal of GEI's Contamination Mitigation theme is to create a central focus and a purposeful enterprise that can draw faculty from across the School of Science, School of Engineering, School of Humanities and Social Sciences as well as Sloan into an area that MIT can and should lead.

From the confluence and integration of fundamental chemistry and biology, technological innovation and design, and the principles of business, policy and economics—all areas of established strength at MIT—emerges the perspective and knowledge base for a new approach to design and synthesis of chemicals, materials and organisms that are essential for economic growth and human welfare.

2.5.2 Research Priorities

In order to meet a goal of developing environmentally safe chemical, material and biological synthesis, we propose product co-optimization at the "research stage". Since synthetic chemists, material scientists and engineers are generally not trained in matters of environmental science and toxicology, meeting this early-stage goal will require a collaborative effort of these professionals with environmental and toxicology specialists. The health effects as a result of exposure to toxic substances are commonly inferred from a variety of sources that require the convergence of expertise from different fields. These include:

- The study of exposed cohorts of organisms (epidemiology)
- Animal experiments (in vivo toxicology)
- Bacterial or other assay systems (in vitro toxicology)
- Structure-activity relationships between chemical composition and harm

Many different areas of expertise need to be brought together in order to assess short-term and long-term environmental and health consequences. These range from environmental transport theory, to environmental fate and transformation modeling, to exposure assessment, to toxicology, epidemiology, and molecular biology. The role of these collaborators would be to obtain advance estimates of discharges, to make forecasts of exposures, and to estimate resultant risks to specific organisms and associated groups of organisms collectively connected by co-occurrence in ecosystems.

Given the goal of co-optimizing synthetic chemical, materials and biological designs for technical performance, cost-effectiveness, and avoidance of ecosystem and human health risks, we need to develop means for efficiently pre-evaluating prospective chemicals, materials and production processes at the earliest stages of their development—at the "research stage'. The approach needs to be dynamic in order to adapt to the evolving nature of new and emerging synthesis demands and practices.

In parallel with efforts toward the prevention and new product development, we should also invest in the development of technology to reduce and/or remove the chemical waste entering our environment as a result of current and/or past technology. Promising approaches include use of new methods for organic synthesis (including the engineering of organisms and/or enzymes, and the use of micro-reactor technology to reduce chemical waste by carrying out synthesis on a smaller scale.

Priority areas for research thus include:

- Improving life-cycle analysis
- Understanding the side products of chemical and material synthesis
- Designing environmentally benign and efficient chemical processes
- Developing of methods to carry out organic synthesis on a smaller scale
- Developing technology to remove pollutants already in the environment
- Developing screening models for environmental exposure
- Developing metrics for synthetic chemical exposure assessments
- Reconciling synthetic chemical use with environmental health
- Devising chemical management heuristics for design

Improving Life-cycle Analysis

Life-cycle assessments that evaluate the prospective material uses for synthetic chemical production must be performed within the context of natural biogeochemical cycles of materials on Earth. Life-cycle analysis should encompass more complex pathways such as biological conversion and phase behavior (e.g., formation of aerosols and particulates from gases, partitioning between organic and aqueous phases, sorption onto soil particles and sediment particles), which pose some fundamental scientific and technological challenges that can only be addressed with collaboration among scientists and technologists. Expertise from different science and engineering fields must be brought together in order to assess how chemicals and materials accumulate in humans and in the environment, how are they biologically, chemically and physically transformed in the human body and in other organisms, and how they disrupt or damage genetic material.

Understanding the Side Products of Chemical and Material Synthesis

The side products of chemicals and materials synthesis need to be identified at the research stage. This entails application of new analytical chemistry tools that not only assess the traditional yield metrics of a particular synthetic pathway, but also elucidate and quantify the diverse array of associated substances that will be co-synthesized and likely discharged. These include side-products associated with catalysts too. Together with information on the likely growth of a synthetic compound production (dependent on perceived use), estimates of the environmental release of this chemical and associated side products should be developed.

Designing Environmentally Benign and Efficient Chemical Processes

Redesigning chemical processes to be efficient and environmentally benign. New processes use alternative and innovative pathways to achieve synthetic reactions or minimize the amount of reagents required to promote the desired transformation. These include the incorporation of catalytic converters that reduce emissions and byproducts, enzymes that can aid in the synthesis of pharmaceuticals and medically-relevant products, new separation membranes that perform effectively without heavy reliance on catalysts, use of temperature and light in lieu of chemicals in synthetic reactions.

Developing of Methods to Carry Out Organic Synthesis on a Smaller Scale

Limiting the production of environmentally unfriendly organic waste as well as limiting the requirement for starting material, 98% of which is derived from Petroleum. The development of micro-reactor technology for organic synthesis has the potential to revolutionize the chemical industry. The environmental benefits of this more efficient method for organic synthesis are considerable if this technology provides cost effective and can meet production demands.

Developing Technology to Remove Pollutants Already in the Environment

Designing innovative methods to remove or sequester existing pollutants. While prevention is desirable, damage to our environment has already been done. New processes that arise from chemical or biological discoveries may be adapted for environmental remediation. Examples include use of engineered bacteria remediate contaminated areas.

Developing Screening Models for Environmental Exposure

We need to develop "screening models" to estimate environmental exposure fields (i.e. changing concentrations in space and time) from release information. This effort must utilize experience in transport (e.g., atmospheric, ground water, coastal sea water, etc.), in phase partitioning, in abiotic reactions, photochemical reactions, and biological (especially microbial) transformations to develop expectations for chemical presence in diverse environmental systems that we all rely on from various discharge scenarios. Much of this work needs to be accomplished using only information on proposed chemical and material structure as close as possible to the 'research stage.'

Developing Metrics for Synthetic Chemical Exposure Assessments

Consistent, systematic metrics to assess the potential impacts of varying exposures to synthetic chemicals on environmental and human health need to be developed. Such toxicities not only include evaluation of ill health to humans and other species (e.g. as was the case for DDT), but also must examine ecosystem health since this platform serves to maintain many critical services (e.g. nitrogen fixation). As for the exposure pre-assessment effort, much of this work needs to be done using only information on proposed chemical structure as early in the chemical design process as possible.

Reconciling Synthetic Chemical Use with Environmental Health

Bringing our decisions to use synthetic chemical choices in line with the goals of long-term human and ecosystem health, along with more typical technical and economic/employment considerations. Optimizing future synthetic chemical designs will not be achieved unless the designers and producers can benefit, on both the short and long term, by simultaneously meeting the three types of needs: technological, economic and environmental.

Devising Chemical Management Heuristics for Design

Developing decision-making approaches for identifying and evaluating opportunities for the design and adoption of environmentally sounder and inherently safer chemicals, materials and processes. These include the identification of alternatives through technology options analysis and incentives for businesses to engage in design and technology substitution.

2.5.3 Organization and Development

Research and education activities within GEI's Contamination Mitigation theme will draw on intellectual resources from across many departments and organizations at MIT, including: the Departments of Chemistry, Chemical Engineering, Biology, Biological Engineering, Physics, Civil and Environmental Engineering, Urban Studies and Planning, and Earth, Atmospheric and Planetary Sciences; the Center for Environmental Health Sciences; the Engineering Systems Division; and the Sloan School of Management. While these activities will launch with the significant momentum and resources of these participating organizations, additional resources will be needed to realize their full potential. Necessary support for new programs common to all GEI themes includes: graduate and post-doctoral fellowships, undergraduate research opportunities, ignition grants, visiting faculty, essential facilitative administrative support, and targeted community-building and outreach activities.

Finally, faculty development in certain priority areas of research expertise would also enhance the ability of activities within GEI's Contamination Mitigation theme to reach their full potential. These areas include:

- *Predictive Eco-toxicology*—a hybrid of life sciences and biological engineering expertise focused on evaluating the likely biological effects of exposure to new synthetic chemicals, including transformations to more or less toxic products. This priority research area is particularly complementary to the departments of Biology and Biological Engineering, in association with the Center for Environmental Health Sciences
- *Computational Chemistry and Chemical Design*—quantum methods for estimating physical-chemical properties, reactivities in diverse media including in aqueous solutions, and toxicological interactions; and developing screening models and flexible codes to evaluate diverse range of chemical discharges to the environment. This priority research area is particularly complementary to the departments of Chemistry, Chemical Engineering, Materials Science and Engineering, and Physics
- *Green Organic Chemistry*—synthetic organic expertise combined with toxicology focused on the processes of making molecules. This priority research area is particularly complementary to the departments of Chemistry and Biological Engineering, in association with the Center for Environmental Health Sciences

2.6 Sustainable Societies

The last ten years have seen an explosion of interest in the concept and practice of sustainability, from municipal governments to multi-national corporations. The reasons are clear and widely acknowledged: resource use and waste generation created by current human economic activity already exceed the sustainable carrying capacity of the planet. This imbalance is worsening as world population is projected to grow from nearly 7 billion today to about 9 billion by 2050—with well over half that number striving to rise out of poverty. For them to succeed will require greater energy use and material consumption, all while developed nations continue to promote their own continued economic growth. Rapid urbanization is accompanying this growth, placing intense strains on infrastructure, services, and environmental quality in cities around the world. Fully half of the world's current population of nearly 7 billion lives in urban areas. In the developed world, the figure is closer to 80 percent. Demographic projections indicate that global population will grow another 2 billion by 2050, with most of those new people living in the megacities of the developing world. The social, technological and environmental implications of this rapid urbanization are profound.

Even more troubling, the growth in material consumption per capita in the developed world over the last half century has not significantly increased people's subjective well-being or happiness: expectations rise along with incomes and consumption; job quality has declined while work hours have risen, and while time for family, childcare, community, leisure and even sleep has fallen. Furthermore, in the United States and around the world, the gap between rich and poor is expanding, a phenomenon exacerbated by environmental impacts that disproportionately affect marginal populations (e.g. island nations and coastal areas facing sea level rise from climate change, and drought in sub-Saharan Africa).

There is, however, a silver lining to this cloud of socially and environmentally unsustainable development. It may be possible to cultivate sustainable societies—those in which quality of life, social equity, and environmental regeneration go hand in hand. Two strategies weave together in pursuit of that future. The first is the quest for eco-efficiency: policies and investments that enable us to reduce, reuse, and recycle the resources required for human activity. In other words, how can we do more with less? The second strategy is to question and transform what it means to "do more"—to understand the sources of social well-being, and to better orient our governments, businesses, and civil associations towards increasing well-being in lieu of material economic growth that is unsustainable on a finite planet. It may be possible to optimize the ratio of social well-being to environmental impact in ways as yet unexplored.

One key challenge in pursuing this optimization, however, is the need for collective action. While single firms or homeowners can take marginal steps toward sustainability, more fundamental solutions require change on a larger scale: collaboration among diverse organizations and sectors to build coalitions of support; communities collectively adopting new habits and norms; and private and public policies that ensure minimum standards and help overcome systematic market failures. Understanding the dynamics of these changes represents a major research challenge for the social and behavioral sciences.

2.6.1 Opportunity at MIT

Through its Sustainable Societies theme, GEI will bring MIT's significant intellectual resources to bear on these challenges, building on prior interdisciplinary research at the School of Architecture and Planning (SAP), the MIT Sloan School of Management, the Engineering Systems Division (ESD), and the School of Humanities, Arts, and Social Science (SHASS), in collaboration with colleagues in the schools of science and engineering. The Sustainable Societies theme of GEI will take these efforts to the next level. It will support a powerful and necessary conversation across these domains, and amplify our collective impact on policy and practice around the world. Just as MIT has contributed to transformations of the global economy in the domains of quality, productivity, and innovation, we now have a powerful contribution to make in sustainability.

A few overarching capabilities make MIT unique and will characterize work within the Sustainable Societies theme of GEI:

- *Deep engagement between theory and practice that generates timely research and rapid diffusion of knowledge*—SAP, Sloan, and ESD all sustain partnerships with businesses, governments, and NGO's involved in the pursuit of sustainability. Research in SHASS is characterized by deep immersion and knowledge of field sites where natural experiments are occurring and field experiments are possible. The Sustainable Societies theme of GEI will serve not only to focus efforts within MIT, but also attract participation from external partners
- *Systems approaches*—MIT is characterized by mastery of the modeling and optimization techniques necessary to understand and improve complex socio-technical systems. This extends from system dynamics at MIT Sloan, through life cycle and value chain analysis in ESD, material flow analysis in SAP, environmental simulation and prediction capabilities in EAPS and SOE, to deep econometric expertise at SHASS and Sloan. We are uniquely poised to integrate the global systems

understanding of the environment from the other GEI themes into a systems view of human social and economic activity

- *Technological and institutional innovation*—Social science research at MIT has always taken advantage of the unique science and technological capabilities of the Institute, and has examined the institutional context that shapes and is shaped by technological innovation. Bringing these perspectives to bear is essential in orchestrating a shift toward more sustainable technologies. At the same time, MIT social scientists are involved in social and institutional innovations as well, through policy research and field experiments around the globe
- *Commitment to interdisciplinary research*—The community of social scientists at MIT is distinctive in its dual contribution: to the core disciplines of anthropology, economics, history, political science, psychology, and sociology; and to critical problem domains central to sustainability that cross these disciplinary lines

Building on these strengths, MIT has already been, and will continue to be, a critical player in supporting firms' and communities' moves toward environmental sustainability. Along that path, research and education within GEI's Sustainable Societies theme will strengthen, integrate, and enrich current efforts. Inquiry into social well-being as an alternative to material economic growth is more nascent. Although there is strong interest from a variety of senior faculty members on the topic, the leadership GEI through its Sustainable Societies theme will be essential to consolidating that interest and developing a compelling research program.

2.6.2 Research Priorities

A key challenge in optimizing the ratio of social well-being to environmental impact is choosing an appropriate system boundary for research, policy, and practice. GEI takes the global, earth system view of environmental challenges, but values work at all scales relevant to the generation of sustainable societies. Urban studies scholars, for example, use geographic boundaries to analyze the urban metabolism of material goods, and the capacity of local infrastructure to enable pro-environmental practices like recycling. Business scholars examine the factory, firm, or global value chain, permitting a view of the connection between economic activities in locales around the world. Material systems analysts follow the life cycle of particular materials and products as they flow through geographies and supply chains, and analyze the economic and environmental impact at each step. An integrative inquiry about Sustainable Societies must bring together these units and levels of analysis. What are the technical, managerial, economic, legal, and cultural changes that may be needed at each scale? What are the processes through which these changes can be achieved? How do the changes interact with one another?

Four interconnected thrusts of priority research form the foundation of the Sustainable Societies theme (Figure 2.6):

- *Foundational inquiry into social well-being* and its relationship to environmental quality and impact
- *Sector-level sustainability studies* organized around key contributors to well being, e.g.: information and communication; food; housing/shelter; transportation; health and hygiene; security from conflict

- *City-level sustainability studies* that include urban policy analysis; urban form and landscape; resilience and adaptation of communities and the built environment
- *Policy studies* examining the design of policies and institutions across multiple levels (firm, value chain, industry; urban, national, international), the integration of scientific knowledge into policy-making, and the processes of collective action that bring policies into effect

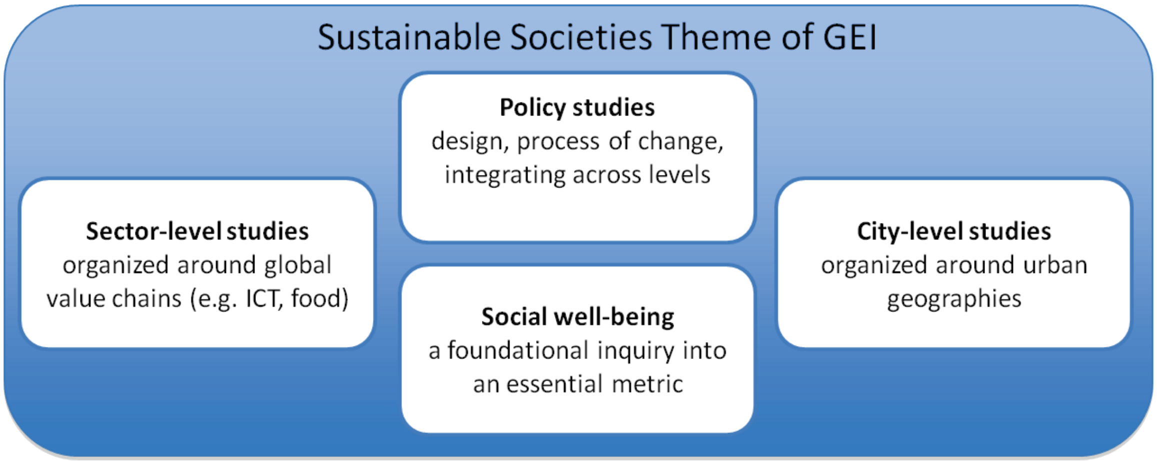

Figure 2.6 Four fundamental thrusts of inaugural priority research within GEI's Sustainable Societies theme.

Taken together, this slate of priority research thrusts constitutes a comprehensive approach to making sustainable societies, in both the developed and developing world. Groups of MIT faculty are already engaged in each topical area, and are prepared to expand the scope of their efforts.

Foundational Inquiry into Social Well-being

Ultimately the purpose of "doing more with less" is to enhance human well-being. But what is well-being? In the modern era we have come to associate advances in well-being with increasing material consumption. Research on subjective well-being (aka "happiness") shows, however, that greater material consumption, beyond the level that provides for basic needs, contributes little to the subjective sense of well-being. Thus, even without environmental constraints, the conflation of consumption and well-being appears to be dysfunctional in developed economies. Further, the erosion of natural resources as a result of such consumption has its own impacts on well-being as aesthetic, recreational, and therapeutic value of healthy ecosystems is lost.

Important research questions here include: How do different regions and cultures understand and experience well-being? What social structures, incentives, and policies contribute to overconsumption and erode personal time for family, community and other valuable non-monetary activities? What dimensions of community and professional life contribute to well-being but are undervalued today?

Today these questions are leading to pragmatic change through businesses creating "healthy value chains;" studies of subjective well-being (hedonics) at the individual, community, organizational and institutional levels; local experiments in alternative production and consumption systems such as Time Banks; and implementing new metrics such as the Gross National Happiness Index in Bhutan and Brazil.

Research examining these efforts will aim to situate them in historical, political, and cultural context. It will draw on MIT's strengths in a variety of disciplines, including economic sociology, political science, history, anthropology, brain and cognitive science, development studies, and others. Such inquiry will guide appraisals of efforts at sustainability, and develop useful metrics for well-being that include both universal and culturally specific elements.

Sector–level Sustainability Studies

Providing for human needs with less strain on natural resources can be accomplished through several different levels of intervention. With each level, the potential for mitigation of environmental impact is greater, but so are the institutional changes required, such as:

- Improving production and provisioning processes
- Substituting materials to reduce environmental impact and improve product performance
- Redesigning products for improved recyclability and use of renewable resources, which can require significant changes in complementary infrastructure
- Functional substitution of product categories
- Transformation of consumption patterns

In creating sustainable societies, it is critical to pursue all these levels. The challenge is that the "quick wins" available through the lower levels can distract from the possibilities at higher levels. Therefore it is useful to organize an inquiry about sustainability around basic human needs and desires around which a variety of functional substitutions and system transformations might be possible: nutrition; shelter; clothing and adornment; transportation and communication; health and hygiene, to name a few.

Based on the convergence of current research strengths and interests at MIT with critical areas of convergence between social needs and environmental sustainability, four inaugural sector-level sustainability studies at MIT are proposed:

- Sustainable Information and Communications
- Sustainable Food and Agriculture
- Sustainable Buildings
- Sustainable Transportation Systems

Sustainable Information and Communications

Information and communications technology (ICT) has become ubiquitous. By the end of 2011, the global fleet of personal computers is expected to surpass 1.5 billion units, and more than five billion mobile phones are in service. The explosion in computing technology creates new opportunities for communication, collaboration, self-expression, entertainment, and political empowerment for people around the world. At the same time, the complex industrial supply chain for these devices is highly resource intensive. In 2010, the global personal computer production industry alone consumed nearly 2 exajoules of energy, with far more implicated in their use. ICT manufacture involves extraction, distribution, and disposal of rare earths and heavy metals that are toxic to human and other life. Approximately 40 million tons/year of electronic waste finds its way to landfills around the world. In the United States alone, it is estimated that approximately 454 million kg of lead will enter the environment in the next 10 years from e-waste disposal.

These realities, and their effects on consumer purchasing decisions and public policy making, have prompted intense interest within the electronics sector to understand the environmental performance of the entire life cycle of ICT products. The interdisciplinary, systems-based approach to research at MIT enable us to tackle research challenges in the ICT sector that span the entire value chain, including:

- Assessing the risks to supply chains from dependence on scarce materials, such as rare earth elements
- Evaluating the key drivers of environmental impact (including climate change, human health, ecosystem toxicity, and resource consumption) throughout the product life cycle through the use of life cycle assessment
- Developing methodologies to streamline the life cycle assessment process for ICT products so that original equipment manufacturers, retailers, and consumers do not need to rely on lengthy and resource intensive assessments each time a new product is developed and released
- Investigating methodologies to incorporate environmental impact information into the ICT design process and evaluate tradeoffs between environmental impact, technical performance, and cost
- Analyzing systems that collect and treat e-waste, including the flow of e-waste across the world and the social and environmental impacts of e-waste processing in developing countries

Sustainable Food and Agriculture

Primary food production provides the livelihoods of billions of people around the globe, and food is the one product that every human literally consumes. The global food system also accounts for significant environmental impacts: 10-12% of anthropogenic greenhouse gas emissions in the form of nitrous oxides, methane, and carbon dioxide; 69% of fresh water use by humans; eutrophication and toxicity of water ways; deforestation and erosion of top soil essential for ecological resilience to extreme weather events. The challenge of feeding 9 billion people in the coming century, sustainably, has provoked a tremendous wave of new research and practice in cultivation, processing, distribution, and preparation of food. Debates rage about the relative merit of genetic modification, chemical pesticides, efficient monocultures, and global distribution vs. organic, small scale, regional, diversified farming. Some agri-business companies and individual cities are already carrying out experiments in sustainable food provision that select and combine these elements of agricultural innovation.

In this context, there are critical roles for MIT to play in realizing a holistic approach to sustainability and social well-being in our food systems, including:

- In collaboration with the Contamination Mitigation theme, evaluating the human and ecological health impacts of new agricultural technologies such as genetic modification
- In collaboration with the Climate theme, analyzing the sensitivity of the global food system to global climate change
- In collaboration with the Water theme, understanding the changes in infrastructure, agricultural technology, management practices, pricing policies, and institutions necessary to meet human food needs in a sustainable way
- Examining global supply chains for food products to identify opportunities to reduce natural resource use (in production, processing, transport, and consumption) through life cycle analysis and supply chain optimization, building on the work of the Center for Transportation and Logistics
- Examining the impact of food production methods on human well-being, from production (e.g., studies of agricultural labor and communities in Political Science and MIT Sloan) to consumption (through studies of nutrition and health)
- Assessing efforts to supply food to low-income neighborhoods and the efficacy of urban agriculture in different settings, building on work in the Department of Urban Studies and Planning
- Understanding how cities in the developed and developing world can strengthen ties between local farmers and urban consumers

One of the notable aspects of the food sector is the way it combines water, energy, and climate change with cultural, political, and economic factors. Food scarcity can have dramatic impacts on health, political unrest, international conflict, migration, and economic well-being, especially in poor areas where food expenses constitute a major portion of household budgets. There is a strong need for an integrated approach in studies of sustainable food production. This approach should be directed toward some basic questions. What are the likely impacts of resource constraints (especially water and land) on regional food production capabilities? What are the economic and social implications of changing import/export patterns (e.g. greater imports by China, which has long been nearly self-sufficient in food)? What are the tradeoffs between using land for renewable energy production and for food production? How can management innovations and technological innovations be best combined to achieve more efficient use of limited resources? How will spatial differences in climate change affect the regional distribution of food surpluses and shortages? What technological advances are most promising for increasing food production and/or reducing the environmental footprint of agriculture?

Such questions will attract increasing attention in the coming decades, as the pressures for increased production, generated by increasing populations demanding better diets encounter countervailing pressures imposed by resource limitations, climate change, and environmental concerns. MIT has the expertise needed to address such questions, as part of an overarching effort to provide an adequate supply of food to everyone on the planet, in a sustainable way that promotes human health and well-being.

Sustainable Buildings

The buildings we inhabit are the most visible manifestation of human society, and account for a tremendous proportion of our environmental impact. Buildings produce 60 percent of U.S. greenhouse gas emissions through direct and indirect energy consumption. Research into sustainable building technologies and policies is based on the premise that properly designed and retrofitted buildings are an enormous potential source of greenhouse gas emission reductions. Work within the MIT Energy Initiative is aggressively exploring these opportunities for energy efficiency. In addition, however, properly designed buildings can retain storm water, contribute to air quality, foster community, and otherwise improve human well-being. These essential aspects of building design can be explored effectively through the Sustainable Societies theme of the GEI. It is also critical to situate efforts at building construction and retrofit in the context of global production systems for the raw materials of construction, with their associated environmental impacts. An MIT-wide inquiry into sustainable shelter means taking this life cycle and holistic perspective.

Key research issues to be addressed in cooperation with the MIT Energy Initiative include:

- Understanding the vulnerabilities of the construction industry to changes in the availability of building materials, including those driven by environmental policy (e.g. forest preservation for wood; carbon emissions from cement)
- Understanding the impacts on human health, comfort, and well-being of building design choices that aim to reduce environmental impact, including lower-toxicity materials and enhanced natural light
- In collaboration with the Water theme, designing buildings and urban water-management systems to conserve physical water systems, balance the needs of aquatic species, protect water-dependent livelihoods, and protect cultural experiences of water
- Developing innovative methods for ventilating buildings as a means of improving indoor air quality
- Investigating the effectiveness of municipal green-building policies and building codes at driving private-sector green building

Sustainable Transportation Systems

Transportation accounts for 25 percent of U.S. greenhouse gas emissions and is a substantial contributor to low atmosphere air pollution. As part of Transportation@MIT, researchers are investigating mechanisms for reducing urban auto dependence and facilitating alternative forms of transportation in urban regions. At the same time MITEI has a robust research thrust in transportation and vehicle systems, which focuses primarily on alternative and renewable fuels and efficient engine technologies, but also integrates with planning and policy. The thrust of the sustainable transportation theme within GEI's Sustainable Societies theme will be to collaborate with Transportation@MIT and MITEI to fully realize MIT's potential to lead in this sector—scientifically, technologically, economically and socially.

Key research issues to be addressed in cooperation with Transportation@MIT and MITEI include:

- Designing alternative, multi-modal and intelligent urban transportation systems
- Understanding the social dynamics, politics and environmental impacts of reducing urban dwellers' dependence on cars through a series of case studies of cities
- Designing policies that create markets for alternative-fuel vehicles that are sustainable not only ecologically, but economically
- Examining mobility patterns and urbanization trends

City-level Sustainability Studies

Using the sector-level approach above, it is possible to realize opportunities for improved well-being and reduced environmental impact across global value chains. To understand the connections between different sector-level systems, however, requires a more geographically, demographically and culturally focused perspective at the urban scale.

Long regarded simply as environmental disasters, urban areas have the potential to achieve significant efficiencies in energy and water use; their ability to facilitate waste reduction, reuse and recycling is also now well recognized. Furthermore, dense, compact urban settlements can minimize human impacts on surrounding land, which provides critical ecological services including clean air and water, wildlife habitat and respite for humans. But if urban areas are to complement rather than derail efforts toward global environmental sustainability, they must be properly planned, designed, built, and governed. Such efforts can also make them more resilient in the face of both natural and human-made disasters.

Based on the convergence of current research strengths and interests at MIT with critical areas of convergence between social needs and environmental sustainability, four inaugural city-level sustainability studies at MIT are proposed:

- Urban Sustainability and Policy Analysis
- Sustainable Urban Form
- Urban Adaptation and Resilience

<u>Urban Sustainability Policy Analysis</u>

In recognition of their critical role in the pursuit of global sustainability, cities around the world have committed themselves to becoming more sustainable. In the U.S. alone, more than 1,000 U.S. mayors have signed the Mayor's Climate agreement, originally proposed by Seattle Mayor Greg Nickels in 2005, pledging to reduce their cities' greenhouse gas emissions by 7 percent below 1990 levels by 2012. Worldwide, thousands of cities have committed to fulfilling the principles of the United Nation's Agenda 21, a sustainable development manifesto. This research agenda asks: What has all this activity amounted to? How effective are urban sustainability initiatives, and why? How can analytic tools, such as urban metabolism analysis, enhance policymakers' ability to craft effective policies? To what extent are the benefits of cities' sustainability efforts distributed equitably among residents? Are those initiatives creating employment for those who need it?

Key research issues to be addressed include:

- Accurately assessing urban resource use intensity (urban metabolism) using the tools of systems dynamics, and agent- and rule-based modeling
- Analyzing the effectiveness of urban sustainability initiatives in the U.S.
- Enhancing municipal capacity, developing a green workforce, and ensuring equitable implementation of urban sustainability initiatives

Sustainable Urban Form

The physical form of the city is critical to its sustainability. Research in the area of sustainable urban form aims to generate knowledge about the key drivers of urban form; to develop designs that are tailored to the features of particular geographies; and enhance techniques for restoring degraded landscapes.

Key research issues to be addressed include:

- Assessing the impacts of standards and codes on urban ecology and sustainability
- Developing advanced tools for modeling, visualizing, and analyzing urban design and planning proposals
- Designing development solutions for a new wetland to begin remediating the effects of massive agricultural and urban pollution issues
- Developing remediation/redevelopment strategies for environmental restoration

Urban Adaptation and Resilience

A critical aspect of efforts to become more sustainable is fostering resilience in the face of disasters and a changing climate. MIT faculty are deeply involved in both planning to minimize the impacts of disaster and helping cities recover from disasters once they strike. MIT researchers also seek to bolster efforts to plan for climate change and its myriad impacts.

Key research issues to be addressed include:

- Conducting international comparative assessments of urban climate adaptation planning
- Designing and testing new ways to help municipalities, regional agencies and national governments engage decision-makers and stakeholders in more effectively managing the risks associated with climate change
- Examining the complex relationship between natural hazards and environmental design to address: 1) anticipatory design for hazards preparedness, 2) retrofit of existing buildings and landscapes, 3) reconstruction of post-disaster landscapes, 4) resettlement in less vulnerable locations, and 5) commemorative design

Policy Studies of Institutional Design and Processes of Change

Sustainable societies cannot be realized without processes of collective action, institutional change, and intelligent policy design—all informed by a scientific understanding of the global environment. There are, however, important general questions about how such efforts can best proceed. Inaugural areas of inquiry for the Sustainable Societies theme of GEI will include key aspects of policy design, institutional change, and technical and institutional potential.

<u>Policy Design</u>

In this research area we will explore three types of policies and institutional designs that have potential for large-scale reduction in environmental impact while improving social well-being:

- The first focuses on information: making the social and environmental impacts of products, companies, and communities more salient to people in their purchase decisions (e.g., through rating systems and certifications)
- The second focuses on prices: policies that change the price of goods to reflect their true costs, including environmental and other externalities (e.g. markets for ecosystem services)
- The third focuses on establishing minimum standards for human rights and environmental health (e.g. limits on toxic substances, labor standards)

Such policies can be implemented through industry self-regulation, NGO-facilitated governance, government policy, and policies created and enforced by combinations of these institutions. We are in a moment of great experimentation around the globe with this wide range of policies and governance mechanisms. MIT can play a pivotal role in both evaluating these experiments and working with practitioners to implement field experiments to test policy innovations.

<u>Institutional Change</u>

Policy design is, however, only half the story. It is equally critical to understand processes of change in socio-technical systems and institutions. How do new practices, policies and institutional designs come to be? How can they be implemented in ways that foster continuous improvement and innovation? What leadership and organizational capacities are required to contribute to institutional change? How can different and often competing organizations, with a history of adversarial relations come together to establish standards, share knowledge, and create consumer awareness needed to develop industries that are sustainable not only ecologically but economically?

This inquiry includes documentation of contemporary and historical change processes, but also exploration of cutting edge practices and technologies such as distributed leadership, cross-organizational learning networks, simulation model-based dialogue, and consensus building.

In particular, it is important to understand what strategies enable simultaneous progress on all of the above domains. For example, consider the development of the United States Climate Action Partnership, a coalition of companies who have made internal progress on eco-efficiency and are now lobbying for a price on carbon that will enhance their competitive position as more sustainable businesses. How did this multi-level change process emerge? How can we design other initiatives so that in addition to reducing environmental impact within particular firms and communities, they build the capacity for collective action among those actors on behalf of industry standards and public policy change? Such questions can be addressed through both the sectoral and the geographical studies described above, which should highlight how changes at multiple levels are occurring.

Technical and Institutional Potential

A variety of scholars have undertaken technical potential studies related to environmental mitigation, which prospectively examine options for the future: the MIT Energy Initiative studies on the Future of Coal, Nuclear Power, and Natural Gas; Amory Lovins' work on the technical potential of energy efficiency; and the MIT Material Systems Lab's analysis of the potential for aluminum recycling to mitigate the impact of virgin aluminum production. Through its Sustainable Societies theme, GEI would augment such technical potential studies with analysis of *institutional potential*: the requirements and potential for institutional change, given our knowledge of effective change strategies. In the aluminum example, this might mean examining where recycling rates are the highest around the world, understanding the operational practices and institutional structures that support those recycling rates (e.g., high consumer participation related to high landfill tipping fees), and the historical processes that produced those outcomes. What is needed to transfer and scale these ideas where recycling rates are currently low? What stakeholders would have to be engaged, and what are viable strategies for doing so? At minimum, such analysis would reveal institutional constraints and a more realistic assessment of technical potential. Ideally, it would help identify pathways for business and policy leaders to accelerate movement toward the technical potential.

Platforms to Enhance Collaboration Among Scientists, Policy Makers and the Public

Building sustainable societies is, of course, far too big a problem for MIT or any other single institution to solve alone. In just the last decade or so, however, new ways of solving global problems have become possible. As examples like Wikipedia and Linux illustrate, it's now possible to combine the work of thousands of people around the world in ways that would have been impossible only a few years ago.

In addition to scientific studies of the problem, therefore, a key research activity within the Sustainable Societies theme of GEI will be developing innovative on-line platforms for facilitating productive collaboration among scientists, policy makers, and the general public. For instance, one such system called the Climate CoLab is already being developed in MIT's Center for Collective Intelligence. In this system, teams from around the world are developing detailed policy proposals for dealing with global climate change that include runs of simplified simulation models. These models are based on state-of-the-art scientific research, and the winning proposals are presented to key policy makers.

This broadly collaborative approach has a number of potential benefits. First, by letting anyone who is interested try to solve real policy problems using the most current research results, this provides a vehicle for communicating scientific results to policy makers and the public and for creating more informed and engaged citizens. Second, it may also provide a platform for scientific collaboration that crosses not only disciplines but also institutions and national borders.

Finally, and perhaps most importantly, by constructively engaging many times more people in problem solving, it may significantly increase the chances that promising new approaches will be considered and better solutions will be found.

In addition to creating such platforms for collaboration, we also expect to study them. For example: What motivates experts, policy makers, and citizens to participate in communities like this in the first place? What kinds of interactions do participants have on the website? How do the attitudes and knowledge of participants change? What factors affect the quality of proposals generated? And what are the pathways through which the proposals affect policy?

2.6.3 Organization and Development

The research objectives within GEI's Sustainable Societies theme will be realized through faculty from multiple schools and departments working on trans-disciplinary issues with a cadre of graduate students and post-doctoral research associates. This will include members of: the MIT Sloan Sustainability Research Group; the Material Systems Lab; the Center for Transportation and Logistics; the School of Architecture and Planning, particularly the Department of Urban Studies and Planning; the Joint Program on the Science and Policy of Global Change; the Center for Collective Intelligence; the Employment Policy Network; the departments of Political Science, Economics, History, Anthropology, and Science and Technology Studies. There are also clear tie-ins with the other GEI's other inaugural research themes in terms of exploring the implementation of policies informed by basic science, and striving to understand the social drivers of environmental change.

To launch each of the four research thrusts described above, we will conduct a series of synthetic literature reviews and seminars to generate the intellectual foundation and interdisciplinary connections needed for high-level collaborative research. These efforts will proceed alongside interdisciplinary pilot projects that ramp up into more intensive work on the sectoral, urban, and policy/institutional studies.

One key output at the culmination of this five-year ramp-up period will be a book and sustained multimedia platform that synthesizes insights gained from across all efforts within the Sustainable Societies theme. In the same way that *Made In America* integrated MIT industry studies toward a national pathway to competitiveness, this "*Made On Earth"* product will integrate sectoral studies toward a global pathway to sustainability. Academic papers will be generated continuously through work within the theme, using the *Made On Earth* platform to assist with dissemination.

In addition, activities within GEI's Sustainable Societies theme will lead to the development of deep engagement with an extended network of policy makers and practitioners outside of MIT. The School of Architecture and Planning and its Department of Urban Studies and Planning similarly hosts a variety of projects related to urban sustainability, in which MIT researchers work in partnership with practitioner groups, local governments, and private-sector clients. MIT Sloan's Sustainability Initiative was launched through the S-Lab (Laboratory for Sustainable Business) which deploys students to companies, NGO's, and government agencies to tackle real-world sustainability problems. Such courses are an entry point for industry partners who develop ongoing partnerships that use MIT as a learning hub through Executive Education and collaborative research. These networks will be indispensible in gaining access to research sites, conducting field experiments, and disseminating insights generated within all of GEI's research themes.

While research and education activities within GEI's Sustainable Societies theme will launch with the significant momentum and resources of the participating faculty, departments and schools, additional resources will be needed to realize their full potential. Necessary support for new programs common to all GEI themes includes: graduate and post-doctoral fellowships, undergraduate research opportunities, ignition grants, visiting faculty, and targeted community-building and outreach activities. Special support will also be needed for the foundational *Made On Earth* project; and, because much of the specific work conducted under the rubric of sustainable societies is directed at an audience of policymakers, additional funding for outreach activities—conferences, webinars, and other media—will be vital.

Finally, faculty development in certain priority areas of research expertise would also enhance the ability of activities within GEI's Sustainable Societies theme to reach their full potential. These areas include:

- *Sustainable Business Practices*—development of business models consistent with sustainable economies and communities, and with a focus across scales—from firms (operations, product development, human resources, finance, etc.) to supply networks (including sourcing, complementary assets, and product end-of-life), to the "ecosystem" of firms, consumers, communities, and other stakeholders that jointly determine overall resource use, waste generation, and well being. This priority research area is particularly complementary to the Sloan School, and the departments of Anthropology and Political Science
- *Urban Environmental Planning*—a combination of scholarship and practical experience in urban environmental planning yielding expertise in the theory and practice of cutting-edge environmental planning, design, zoning and transportation practices from around the world

3. Educational Engagement

The Global Environment Initiative comprises an agenda for research at MIT to advance our understanding of the environment and identify science-based strategies for managing the vital environmental systems on which we depend. This broad research agenda encompasses an inherent and substantial educational footprint, both in terms of curricular and experiential training for students. Simply put, understanding that environmental health and human welfare are inextricably linked, and incorporating that perspective into all scientific and engineering practice, must become a basic part of MIT's basic educational message delivered in the classroom, the lab and the field.

To advance this goal, a GEI Education Task Force will be created to coordinate and enhance environmental education activities and offerings at MIT, and promote them to the student body. Taken together and expanded over time, GEI's ever-evolving commitment to education will ensure the direct impact of its research agenda on the training of future leaders in environmental science, engineering and planning.

3.1 Building on Existing Programs

We propose developing new educational programs within GEI to parallel and complement its research agenda. A number of existing educational programs and initiatives at MIT, as enumerated below, provide a solid foundation from which to build:

MIT-WHOI Joint Program

The MIT-Woods Hole Joint Program in Oceanography and Applied Ocean Science and Engineering is one of the premier graduate training programs for ocean science and ocean engineering in the world. It draws on different strengths of both institutions to provide a unique platform enabling students to work on some of the most challenging science and engineering problems in the world. This program spans theory, observation and instrumentation, modeling and policy while integrating ocean physics, chemistry, and engineering. Clearly it can and should form the foundation for graduate education and training within the Oceans and Climate themes.

The MIT-WHOI Joint Program is also relevant to the agendas of other themes within GEI. For example: the coastal urban environment is a major focus of the Sustainable Societies theme; understanding the effects of global change on the hydrologic cycle—in which oceans play a major role—is major focus of the Water theme; microbial ecosystems in the oceans are an important area of focus for the Ecological Resilience theme; and increasing accumulations of synthetic and trace chemicals in the oceans are a major concern of the Contamination Mitigation theme. Thus it is evident that the MIT-WHOI Joint Program relates to all the major themes of GEI and can be leveraged as a foundation for advancing the educational priorities of the entire Initiative.

Microbiology Graduate Program

The Microbiology Graduate Program is a new, highly interdepartmental program that unites students from various backgrounds and with various interests. The program draws students from several different departments and constitutes a community for them. With this community and its associated departmental partnerships students have access to diverse faculty, labs, and courses across the Institute. This legacy graduate program is an important asset to support the educational dimension of the Ecological Resilience theme. The research agenda is also multi-departmental and the Microbiology Graduate Program is a suitable education platform for it.

Program in Computational Systems Biology

The Program in Computational Systems Biology (CSBi) serves a similar interdisciplinary role as the Microbiology Graduate Program but in the computational and systems biology aspects of microbiology and beyond. Its goal is to provide an interdisciplinary education environment that draws from multiple departments and trains students in high-throughput measurement, multivariate computational analysis, and systematic experimental manipulation. CSBi is an existing education program that will be leveraged to implement the education elements of the Ecological Resilience theme.

MIT Sloan Sustainability Certificate

The MIT Sloan Sustainability Certificate currently attracts a large number of MBA students. The success of this program is built on the notion that there is a fundamental alignment between healthy businesses, healthy environments, healthy societies, and an economy that serves human needs. In this program students learn about ways to transform organizations, markets, and communities to achieve the goals of sustainability in the linked spheres.

Environmental Programs in the School of Humanities, Arts and Social Sciences

The contributions and perspectives of anthropologists, historians and other social scientists comprise a vital complement to the efforts and education of those pursuing environmentally oriented research, and are essential to engaging and informing policy makers and the public. The Global Environment Initiative is committed to nurturing and expanding the critical contributions of SHASS faculty. This effort will expand outward from a focus on two existing flagship programs: the *Seminar on Environmental and Agricultural History*, sponsored by MIT's History Faculty and the Program in Science, Technology and Society; and the *Working Group on History, Environment and Energy*, sponsored by the History Faculty.

Freshman Terrascope

In the undergraduate realm, most notably at the freshman level, Terrascope is a unique program of education and community-building that was launched in parallel with the MIT Earth System Initiative. It has a committed cadre of faculty and staff. The student alumni of this program form a strong sense of community after their freshman year experiences. Terrascope is a successful model that the Global Environment Initiative is committed to supporting and expanding as its flagship freshman-level engagement with the education programs at MIT.

3.2 Building a New Undergraduate Minor

The commitment of MIT students to issues of global environment and sustainability is well established and constantly evolving. In the 1980s, the undergraduate group SAVE (Share a Vital Earth) was the driving force behind the Institute’s now thriving annual Earth Day celebrations. Eventually, SAVE merged with Students for Global Sustainability and several other groups to form Sustainability@MIT, now a vibrant hub of combined undergraduate and graduate student activity that sponsors an annual Sustainability Summit with a national reputation. In 2005, engineering and management students cooperated in creating The Generator, a biannual event fostering collaboration and innovation in energy, environment and sustainability. More recently, student governance at both the undergraduate and graduate levels established highly active subcommittees focused on sustainability. Students are also active in MIT's Campus Sustainability Program through the Green Ambassadors Initiative and representation on the Campus Energy ("Walk the Talk") Task Force.

The Faculty Environmental Network for Sustainability was formed in 2008 to harness and nurture this spontaneous groundswell of student interest and activity by developing a formal undergraduate Minor in Environment and Sustainability. Since that beginning, significant progress has been made toward designing a new minor that will equip MIT graduates to engage effectively on issues of environment and sustainability wherever their lives and careers lead. The ERC agrees that building an understanding of the relationship between environmental quality and human welfare must become an essential part of MIT's educational mission, and we intend that GEI will assist the other stakeholders in bringing the new minor to fruition as part of its own educational agenda.

As currently proposed, the minor includes three concentration areas—Earth System and Climate Science, Human-Environment Interactions, and Environmental Governance. Firmly grounded across all five schools in existing courses that are regularly offered, these three core areas (Figure 3.1) comprise a flexible, multidisciplinary curriculum in which students will be able to build both breadth and depth to complement their major area of study. It is anticipated that the new minor will be governed by a multidisciplinary faculty committee drawing on all five schools and reporting to the recently formed Interschool Educational Council (ISEC).

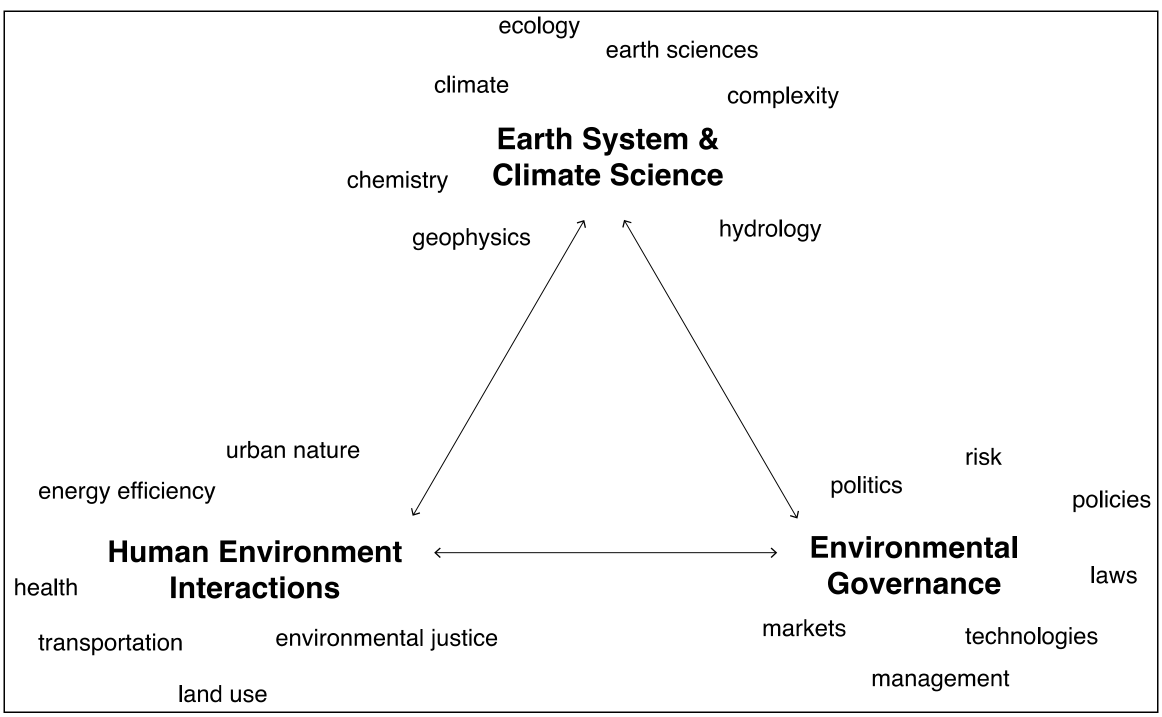

Figure 3.1 Proposed thematic structure for the Minor in Environment and Sustainability.

4. Organization and Administration

GEI will coordinate MIT's environmental research and education activities in much the same way the MIT Energy Initiative (MITEI) serves as the focal point for the Institute's energy activities. Indeed as many human-caused environmental impacts result from energy production and use, GEI will make close collaboration with MITEI a cornerstone of its operation.

Thus GEI will develop MIT's portfolio of environmental research, cooperate with other MIT programs; cultivate new research efforts; and work to recruit new sponsors and donors in collaboration with the MIT Office of Resource Development. The Initiative will allocate ignition grants, sponsor environmental fellows (graduate students, post-docs and visiting faculty) and manage internal and external communications. Hosting workshops and symposia that engage faculty and research staff from across disciplines will be another priority for GEI. With these GEI will foster the development of new research themes, explore synergies between themes and build a truly multidisciplinary community of environmental research at MIT.

Although distinct in their mix of research priorities and participating faculty, GEI's six inaugural research themes are complementary and their activities will be fully coordinated through the Initiative. Neither these nor any future themes will be separate administrative entities. Indeed, the research agendas of all of GEI's major themes will always be interconnected and synergistic. While the six inaugural themes do vary in their degree of present development—from well established programs to relatively nascent research themes—any healthy research enterprise needs a mixture both to thrive over the long term. As is always the case at MIT, the vitality of any given research theme will depend ultimately on the energy, interest and participation of faculty, sponsors and donors. The Global Environment Initiative will be no exception.

The senior administration of GEI will consist of a director and deputy director appointed from the faculty by the Provost, and an executive director hired by them. As GEI grows, additional staff will be added as needed, including: a financial/administrative officer to manage daily operations and accounting, a communications specialist to provide writing and web support, and one or more administrative assistants as warranted. An Environmental Council, consisting of faculty representatives from all five schools at MIT, will advise GEI's senior administration and participate as appropriate on education, outreach and development projects. Additional strategic guidance will be provided by an External Environmental Board to be recruited by the President and Provost in coordination with the Environmental Council. Proposed organizational diagrams for GEI during its start-up phase (Figure 4.1) and once it has reached full-scale maturity (Figure 4.2) are presented below.

Because many human impacts on the environment result from energy production and use, GEI will work closely with (MITEI). In vision and scope, the GEI is designed to complement MITEI, and will make close collaboration a cornerstone of its operation. In order to manage areas of overlap, a steering committee operated jointly by GEI and MITEI will assess how best to address them cooperatively.

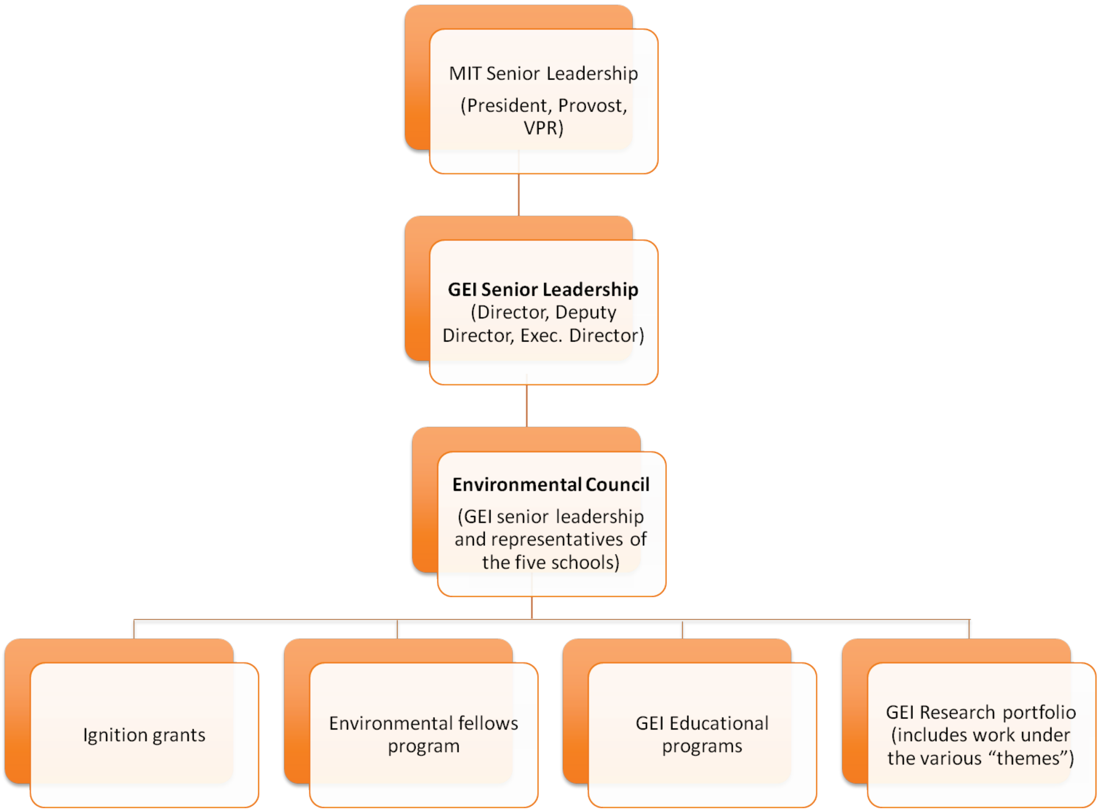

Figure 4.1 Proposed organizational structure for GEI during the start-up phase.

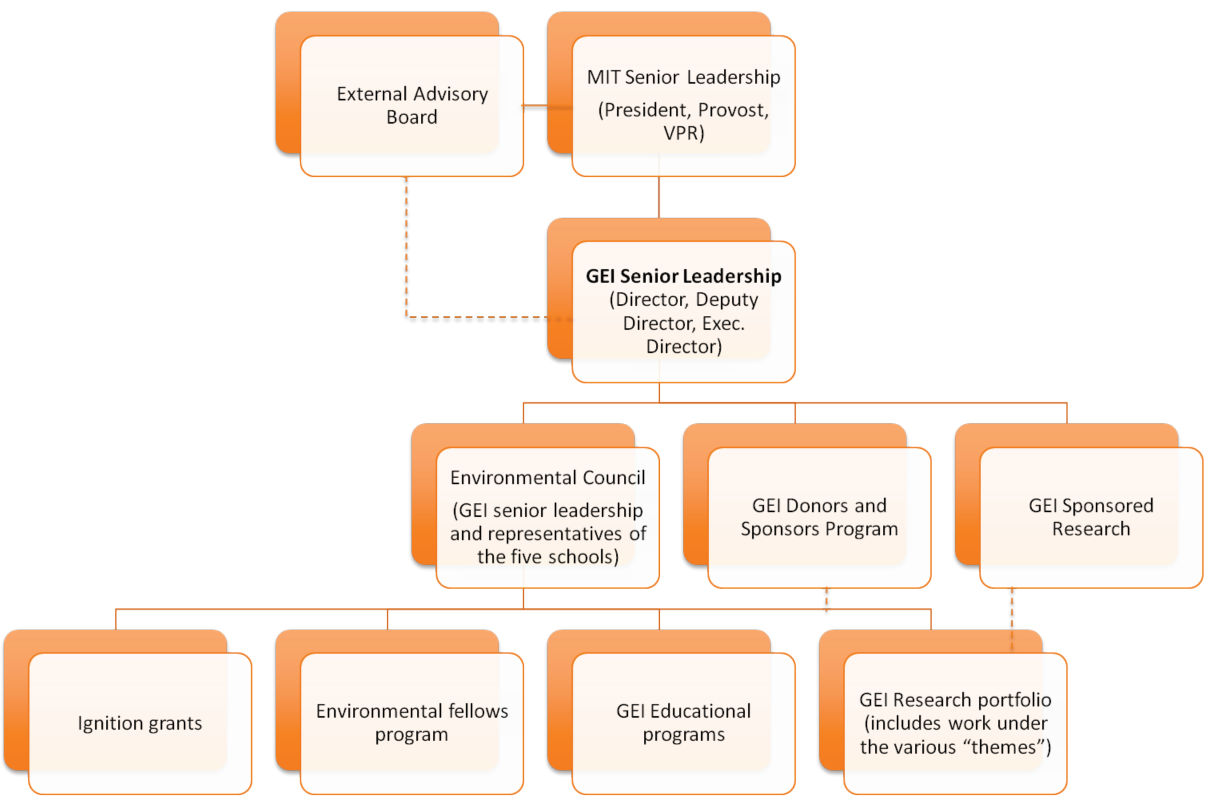

Figure 4.2 Proposed organizational structure for GEI at full-scale maturity.

5. Implementation and Resourcing

Formed from a diverse group of faculty and aided by a variety of broader Institute inputs (workshops, concept paper calls, etc.), the ERC has carefully examined the entire environmental problem-space and identified a strategic research themes that represent the convergence of MIT strengths and potential with key environmental challenges facing humanity. The portfolio of research emphases will naturally evolve over time, but the research priorities identified in Section 2 represent a strong foundation for immediate impact and future growth.

Implementation of GEI will be gradual, with the financial resources required increasing as the initiative demonstrates its value over time. The GEI research themes will develop at different rates according to the interests and efforts of the affiliated faculty. Since they are designed around ongoing research, the GEI research themes will require no new funding to begin work.

The central office of GEI will require modest startup support—salaries, space, services, equipment, and materials—some of which will be inherited from the Earth System Initiative (ESI). To achieve its full potential, however, GEI must attract new resources to support programs and activities common to all the research themes. Therefore, the executive and senior faculty directors will focus on securing external funding to support targeted graduate and post-doctoral research fellowship programs, an ignition grant program to jump-start new research, a communications and outreach program to deliver that research, visiting and professor-of-practice programs, and tenure-track faculty development.

Securing support for the research fellowship and ignition-grant programs will be the top priority, as these are essential to the success of GEI's early development. Additional programs will be phased in as funding becomes available. The addition of new research themes will be driven by faculty commitment and encouraged through fellowship and ignition-grant support.

Graduate training fellowships are very effective mechanisms to implement the research goals identified in the Initiative. The fellowships will provide the mechanism by which research priorities that require initial ignition to get started. Many of the priority research questions identified within the major themes of GEI are new and lie at the frontiers of knowledge, often spanning across disciplines and demanding diverse expertise to address. The graduate training fellowships allow the ignition of these topics by providing participating faculty with the energy, capabilities and fresh perspectives of new students.

Ignition Grants further serve to bridge this gap between inspiration and demonstration, allowing creative researchers from across MIT to collaborate in exploring new ideas and generating the proof-of-concept results needed to attract sustained funding from more traditional sources. That is the goal of the program—to incubate innovative research projects of great potential so that they can become self-sustaining and fulfill their promise. Through its very existence and vitality, the Ignition Grant Program at GEI acts as both a catalyst and an accelerant for creative thinking and cross-disciplinary collaboration. A prototype program was proven successful at MIT by ESI, which has awarded a number of small ignition grants to faculty for high-risk/high-return work in areas with no traditional sources of sponsored research funding. Through the ignition grants faculty essentially 'create' that space in the sponsoring agencies by providing proof-of-concept for an idea and by demonstrating its potential value. Ignition grants under ESI returned an average of $16.30 in sponsored research follow-on funding for every dollar invested in an ignition grant. This success can be replicated by GEI and scaled it to its full potential.

In addition to resources needed for programs common to all the research themes, some themes also have unique resource requirements. As examples: for the Climate theme GEI needs numerical simulation and computer coding specialists to support and improve its flagship Integrated Climate System model, as well as support to co-fund (with federal agencies) the acquisition of innovative biogeochemical, trace gas and aerosol instrumentation and computational equipment (see Section 2.1.3); for the Oceans theme GEI needs support for oceanographic research campaigns to jumpstart the deployment and testing of new sensing technologies, as well as for annual joint faculty meetings between MIT and WHOI (see Section 2.2.3); for the Water theme GEI needs support for the installation, maintenance and staffing of a state-of-the-art water chemistry laboratory to serve as a vital facilitator of both research and education at MIT (see Section 2.3.3); and for the Sustainable Societies theme GEI needs resources for specialized outreach activities to support a foundational study on the parameters of global societal sustainability that will culminate in the book *Made On Earth* (see Section 2.6.3).

While certainly ambitious, this investment in the future by MIT is one that promises handsome dividends in terms of sponsored research quality and volume, faculty development, student education, Institute prestige, and cutting-edge research to enhance human welfare. The plan to sustain GEI's operation and growth beyond the initial five-year period includes: (1) growing the annual sponsored research volume of GEI-affiliated faculty; (2) securing continued external support through ongoing resource development activities; and (3) developing a dues-paying affiliates program of external organizations that value the opportunity to access the cutting edge of environmental knowledge.

This three-pronged approach to fiscal sustainability for GEI is reasonable. After five years of investments in research fellowships, ignition grants and new faculty hires, GEI as the DLC for environmental research initiated through it will be responsible for a very substantial portfolio of new sponsored research paying full Institute overhead. Continued resource development efforts, spearheaded by GEI's Senior Faculty and Executive Directors in cooperation with the Institute's Development Office and fueled by the Initiative's growing relevance in the global environmental arena, also hold significant promise. Finally, there is potential to build one or more dues-based GEI affiliate programs, similar to those now successfully operated by the MIT Energy Initiative and the Joint Program on the Science and Policy of Global Change, as corporations and governments increasingly come to recognize the value sound, cutting-edge environmental intelligence.