MIT ESD

Massachusetts Institute of Technology
Engineering Systems Division

ESD Working Paper Series

The Earth as an Engineering System: Addressing Sustainability through Science, Technology and Policy

Noelle E. Selin
Engineering Systems Division and
Department of Earth, Atmospheric and
Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139 USA
selin@mit.edu

Carey L. Friedman
Center for Global Change Science
Massachusetts Institute of Technology
Cambridge, MA 02139 USA
clf@mit.edu

Paper submitted for the Third International Engineering Systems Symposium (co-sponsored by CESUN, ESD, and TU Delft), to be held June 18-20, 2012 at TU Delft.

ESD-WP-2012-06 March 2012 esd.mit.edu/wps

Third International Engineering Systems Symposium
CESUN 2012, Delft University of Technology, 18-20 June 2012

The Earth as an Engineering System: Addressing Sustainability through Science, Technology and Policy

Noelle E. Selin[1] and Carey L. Friedman[2]

[1]Engineering Systems Division and Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139 USA
[2]Center for Global Change Science, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

selin@mit.edu, clf@mit.edu

Abstract. *We combine insights from the two emerging fields of engineering systems and sustainability science to develop an analytical approach for understanding and managing coupled natural and human systems. The Earth system is characterized with reference to the attributes of engineering systems (real-world existence, artificiality, dynamic properties, hybrid state, and some human control). We argue that human influences have become so overwhelming that it is impossible to understand global Earth systems without taking into account both technical and social dimensions. Aspects of sustainability systems that fulfill functional types of engineering systems are enumerated with reference to five processes (transporting, transforming, storing, exchanging and controlling) and operands (living organisms, matter, information, energy and money). Building on methods from sustainability science, we introduce the concept of Spatial-Temporal-Functional (STF) analysis for addressing sustainability problems in an engineering systems context. We illustrate this framework with reference to the case of global transport of hazardous chemicals. Our analysis suggests that efforts to address cross-scale problems should focus on enhancing mechanisms for transforming and exchanging in addition to controlling.*

Keywords. *Sustainability science, scale, pollutants, governance*

1 Introduction

Sustainability is a key defining challenge of our time. Of the fourteen "grand challenges of engineering" selected by the U.S. National Academy of Engineering in 2008, six are directly related to sustainability (solar energy, fusion energy, carbon sequestration, clean water, nitrogen cycling, and urban infrastructure). Sustainability has been identified as a core, overarching design principle in the emerging field of engineering systems (Cutcher-Gershenfeld et al., 2004) and one of the emerging "-ilities" (de Weck et al., 2011).

The field of sustainability science as an academic endeavor has also emerged over the past few decades (Clark, 2007). Like engineering systems, it focuses on “use-inspired basic research” (Stokes, 1997). Core research questions in sustainability science include: How can dynamic nature-society interaction, including lags and inertia, be better incorporated in models? How do long-term trends, such as consumption and population, reshape nature-society interactions? What determines vulnerability or resilience of the nature-society system under particular conditions? How can research, monitoring, and assessment be better integrated to guide transitions towards sustainability? (Kates et al., 2001)

This paper illustrates connections between the emerging disciplines of engineering systems and sustainability science, with the goal of developing analytical frameworks and methodologies to more effectively address sustainability problems through science and engineering analysis. Section 2 situates the challenge of managing the Earth, as a coupled natural and human system, within the intellectual domain of engineering systems. Section 3 illustrates the methodological potential of linking these two domains, introducing a new concept of spatial-temporal-functional (STF) analysis. In Section 4, engineering systems analysis of a sustainability problem is illustrated through a case study of global transport of persistent pollutants. Section 5 concludes by assessing how engineering systems and sustainability science might be integrated as intellectual domains.

2 The Earth as an Engineering System

Engineering systems are defined as those that fulfill important societal functions, and are categorized by a high degree of both technical and social complexity. De Weck et al. (2011) define five characteristic attributes of engineering systems: real-world existence, artificiality, dynamic properties, hybrid state, and some human control. Further, they classify engineering systems into functional types, categorized by five processes (transporting, transforming, storing, exchanging and controlling) and operands (living organisms, matter, information, energy and money). Characterization and classification of the Earth as an engineering system depends on its fulfilling these attributions and functional types, which are discussed in the following subsections.

2.1. Characterization

Of the five characteristic attributes of engineering systems, in their application to the Earth system, real-world existence is clearly fulfilled by definition. Artificiality, human control, dynamic properties, and hybrid state are discussed below.

Artificiality. The classification of engineering systems as by definition artificial would seem to preclude consideration of the Earth system. In fact, early efforts to define engineering systems judged these "natural" systems, including the Earth's climate, to be outside the scope of engineering systems analysis (Magee and de Weck, 2004). While truly natural systems with little to no human control are not engineering systems, sustainability science research has conclusively shown that the Earth system is not only human-influenced but human-dominated. Vitousek et al. (1997) surveyed the extent of human influence on the Earth, noting that, for example, up to half of the Earth's land surface has been transformed by human action, that humans are the dominant influence on the global nitrogen cycle and other biogeochemical cycles, and that half of all accessible surface fresh water is used by humans. With respect to the climate system, the global average temperature is warmer by 0.8°C than before human influence, due to anthropogenic releases of greenhouse gases such as CO_2. Lubchenko (1998) argued, "We are modifying physical, chemical, and biological systems in new ways, at faster rates, and over larger spatial scales than ever recorded on Earth," terming the human influence a grand planetary experiment. The degree of human influence on the Earth is perhaps best reflected by the concept of the "Anthropocene," proposed by Paul Crutzen as a term to define the present, human-dominated geological epoch (Crutzen, 2002). The term has been considered by geologists as potentially defining a formal epoch. This would mean that the Holocene, the epoch following the Pleistocene and encompassing roughly 10,000 years before the present day, is now officially over (Zalasiewicz et al., 2008).

Human Control. A related question to artificiality is whether these systems are controlled by humans intentionally ("designed") or merely evolved. Consistent with other engineering systems, the coupled human-environment system is partially designed and partially evolved. Areas such as agriculture, forestry, and mining are large-scale designs to transform the Earth for human use. While originally, human disruptions to biogeochemical cycles represented unintended consequences of human activity, their continuation is (if not intended) at least conscious of consequences.

Dynamic Properties. The state of the Earth changes with time. In addition to the anthropogenic-driven changes outlined above in the section on artificiality, the system itself is characterized by dynamic cycles, such as glacial-interglacial transformations and climate modes such as the El Nino/Southern Oscillation phenomenon.

Hybrid State. Much recent research in sustainability science has focused on the concept of "tipping points" or tipping elements in the Earth System (Schellnhuber, 2009). One example of this is the potential instability of the

West Antarctic Ice Sheet in the face of continuing climate change (Lenton et al., 2008).

2.2. Classification

Table 1 presents characteristics of the Earth as a coupled human-natural system, classified according to the functional types of engineering systems. As shown in the table, aspects of sustainability systems fill all the functional types of more traditional engineering systems.

Transforming. Coupled human-natural systems transform the very nature of living organisms through biotechnology (the creation of genetically modified organisms) and through the so-called "Green Revolution" in agricultural productivity (Evenson and Gollin, 2003). Transforming matter is shown through pollutant formation (human activities emit nitrogen oxides and volatile organic compounds, thereby mediating the atmospheric formation of ozone) (Seinfeld and Pandis, 2006) and/or by humans serving as a causative agent in soil formation (Richter, 2007). Another example is nitrogen fixation, mentioned above, with humans being the dominant influence on the global nitrogen biogeochemical cycle. Development of biofuels such as ethanol harnesses the natural process of photosynthesis to transform energy into forms usable by humans (Farrell et al., 2006). Adaptive management techniques use ecosystem management as experiments to transform information from system observations into actionable knowledge (Lee, 1999). Microfinance facilitates the transformation of money into sustainable technologies (Ramaswami et al., 2007).

Transporting. Human activities transport living organisms across the world, for example influencing far-flung ecosystems through the spread of invasive species such as the zebra mussel (Mooney and Cleland, 2001). Pollutants that humans emit to the atmosphere represent matter that is transported worldwide. Human-designed energy systems alter the natural landscape through drilling and pipelines for fossil energy, and contribute to human development; humans may attempt to reverse this process through carbon sequestration. Technical assistance activities, such as those conducted by organizations such as UNITAR, transport information on new technologies and pollution control strategies to assist in capacity-building worldwide. Similarly, organizations such as the Global Environment Facility facilitate monetary transfers from developed to developing countries.

Storing. In the context of policies on climate change, forest carbon sinks store living organisms for human benefit. Similarly, carbon capture and storage efforts prevent matter in the form of CO_2 from reaching the atmosphere (Anderson and Newell, 2004). Hydropower and battery development represent sustainability efforts for storing energy. Sustainability-relevant information storage is facilitated by policy innovations such as pollutant release and transfer registries (PRTRs) (Kerret and Gray, 2007). Carbon offsets, where they have financial value, can be viewed as storage of funds (Bumpus and Liverman, 2008).

Exchanging. The idea of ecosystem services focuses on the resources provided by natural systems to humans, a process of exchanging living organisms (e.g. fisheries) or matter (e.g. fertilizer) for human benefit (Costanza et al., 1997). Information exchange is a key goal of international organizations to facilitate efforts such as chemicals management. In emission trading markets, such as the European Union's Emission Trading System, money is exchanged as a mechanism to support limits on carbon emissions (Ellerman and Buchner, 2008).

Controlling. Most efforts to manage environmental problems focus on controlling. Controlling living organisms and/or matter are the focus of numerous international environmental agreements, such as the Convention on Biological Diversity and the Framework Convention on Climate Change. The principle of Prior Informed Consent (PIC) aims to control information, by providing guidance for countries before agreeing to import potentially hazardous substances or wastes (Krueger, 1998).

Table 1. Sustainability systems classified by engineering system functional types.

Process	Living Organisms (L)	Matter (M)	Energy (E)	Information (I)	Money ($)
Transform	Biotechnology, Green Revolution	Formation of air pollutants; soil formation	Biofuel development	Adaptive management	Microcredit systems
Transport	Invasive species	Atmospheric transport of pollutants	Oil/gas pipelines, electric grid	Technical assistance	Global Environment Facility
Store	Forest carbon sinks	Carbon capture and storage	Reservoirs, batteries	PRTRs	Carbon offsets
Exchange	Fisheries	Ecosystem services	Energy markets	UNEP's Infoterra	Emission trading
Control	Convention on Biological Diversity	Framework Convention on Climate Change	Hydropower, nuclear	Prior Informed Consent (PIC) procedures	Environmental taxes and fees

3 Spatial-Temporal-Functional (STF) Analysis

Given the classification of the Earth as an engineering system in the previous section, we explore the methodological utility of connecting the fields of engineering systems and sustainability science. We build upon a method used in sustainability science literature to illustrate spatial and temporal scales of coupled human-natural systems, the Stommel diagram, and extend it to encompass the functional types of engineering systems.

Stommel (1963) used a figure comparing the spatial and temporal timescales and frequencies of oceanic dynamics to illustrate the complex interactions of scale in the system, with the purpose of informing experimental design. The history of the Stommel diagram, and its subsequent uptake into the field of ecology, is traced by Vance and Doel (2010). In sustainability science, Clark (1985) used a Stommel-type diagram to examine the temporal and spatial scales of climate impacts, integrating analysis of climatic, ecological and social processes. Extensions of the diagram have been adapted to look at the links between social and ecological systems. Westley et al. (2002) plot log of time vs. log of number of people to illustrate cross-scale dynamics in social systems. Selin (2011) used a modified Stommel diagram to illustrate complexities in global mercury pollution science and policy, showing that aspects of the mercury problem that fall between the spatial coverage of major political scales, and beyond the temporal scale of human action, are not presently addressed.

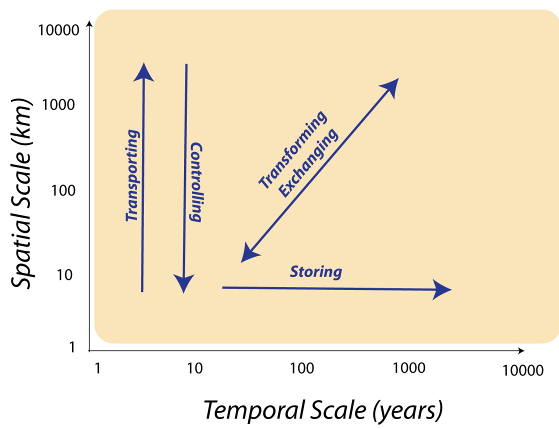

Fig. 1. Spatial-Temporal-Functional (STF) system diagram.

Figure 1 extends the concept of a Stommel diagram to illustrate functional characteristics of engineering systems, and their hypothesized relationships to spatial and temporal scale. We refer to this hybrid concept as Spatial-Temporal-Functional (STF) analysis. As shown in the figure, the process of transporting moves an operand (living organisms, matter, etc.) to a larger spatial scale. Controlling represents the opposite – preventing or limiting spatial extent. Storing, similarly, enables an operand to span temporal scales.

While processes of transporting, controlling and storing move operands in axial dimensions, transforming and exchanging can involve changing both spatial and temporal dimensions. When applied to a particular issue area, this framework suggests potential ways forward in addressing the effectiveness of environmental interventions (Section 4).

4 Global Contamination by Chemicals

The case of global contamination by persistent chemicals provides an illustration of (Section 4.1) the classification of a coupled natural-human system problem as an engineering system, and (Section 4.2) the application and potential utility of STF analysis in an area that links technical knowledge and management.

The commercial manufacturing of human-created organic chemicals began in the 1920s, and production, use and trade of these substances rose sharply after World War II, driven by agricultural, health and industrial development. Public warnings about the environmental effects of hazardous chemicals such as the pesticide DDT and the industrial chemical PCBs emerged in the 1960s and 1970s. By the 1980s and 1990s, it began to be widely recognized that these substances were long-lived in the environment, accumulated in living organisms, and posed a toxic risk to humans and the environment at locations far from their use or release (Selin and Eckley, 2003). A global management system has emerged to address the problem of chemicals in the environment (Selin, 2010).

4.1 Global chemical distribution and management as an engineering system

The technical and policy aspects of the global chemicals system have been described in detail elsewhere (e.g. Selin, 2010; Selin, 2006; Wania and Mackay, 1996). Here, we focus on the utility of the engineering systems concept in more accurately describing its content and function.

Table 2 explores the ways in which engineering systems analysis can illustrate the complex, interacting elements of the chemicals case. With respect to *transforming*, environmental processes can change the form of chemicals in the environment (Schwarzenbach et al., 2003), sometimes producing more toxic products due to environmental reaction. Chemicals themselves transform humans and the natural environment (living organisms) by exerting toxic effects such as carcinogenicity, and transforming biology, disrupting human and wildlife endocrine systems by mimicking hormones. Energy is required in chemicals production, and some POPs are emitted as byproducts of fossil fuel usage. Global assessment of chemicals transforms information from the scientific realm and packages it for policy use (Selin and Eckley, 2003). Money is necessary to facilitate transformation in the case of remediation, which transforms chemicals into less hazardous forms. *Transporting* of chemicals can occur through physical processes in the atmosphere and ocean (matter) (Wania and Mackay, 1996), migratory species (living organisms), or as contaminants in fuel (energy). *Storage* of pollutants can be in the physical environment (sediments/oceans) (Lohmann et al., 2006), by living organisms in the form of bioaccumulation, or in social systems (pesticide stocks). Bioaccumulation of POPs occurs in lipids, and fat storage in organisms represents energy reserves. Living material is stored for future analysis in specimen banks, and PRTRs store information on chemical flows in society. *Exchanging* could refer to the chemicals themselves, which may be in international commerce as hazardous substances or as contaminants in food, such as fish (Shaw et al., 2006). Chemicals are released when nursing mothers provide energy to babies in the form of breast milk (Trapp et al., 2008). Information exchange occurs through PIC procedures in the chemicals area, as noted above, and exchange of money through the Global Environment Facility, which at present serves as the major funding mechanism for the Stockholm Convention. *Controlling* is the main function of institutions in the chemicals area, such as the Stockholm Convention, which proscribe restrictions on chemical production, use and emission.

Table 2. Functional types of engineering systems represented by chemicals case.

Process	Living Organisms (L)	Matter (M)	Energy (E)	Information (I)	Money ($)
Transform	Carcinogenicity, toxicity, endocrine disruption	Chemical reactions	Chemicals production, emissions	Global assessments	Costs of remediation
Transport	Migratory species	Atmospheric/oceanic transport	Contaminants in fuel	Models and simulations	Financial assistance
Store	Human concentrations	Sediments, oceans; pesticide stocks	Bioaccumulation	PRTRs	
Exchange	Contaminated food in commerce	Trade in hazardous substances	Contaminants in breast milk	Prior Informed Consent (PIC) procedures	Global Environment Facility
Control	Dietary advice	Stockholm Convention	Co-benefits for pollution of limiting fossil energy	Proprietary information	POPs fund

Expressing the global chemical system as an engineering system draws particular attention to the linkages and interactions between more physical operands (living organisms, matter, and energy) and those characteristic of management systems (information, money). Informing global efforts to manage hazardous chemicals is the subject of much technical analysis; however, most assessments in the scientific literature focus on transformation and transportation processes involving living organisms, matter and energy. For example, the International Panel on Chemical Pollution aims to link knowledge to action by collecting scientific knowledge about chemical pollution problems and disseminate it to policy-makers and the public (Scheringer et al., 2006). Evaluations of management, in contrast, focus on controlling, with emphasis on the information and monetary aspects.

4.2 STF analysis applied to chemicals

STF analysis of the chemicals problem suggests several ways forward for addressing chemical pollution. Illustrated in Figure 2 (black text) are technical characteristics of the chemicals problem involving matter, living organisms, and energy, which span multiple spatial and temporal scales. Overlaid in blue are the temporal and spatial dimensions of aspects of policy, which largely involve information and money. Some POPs, such as PAHs, are shorter-lived in the atmosphere and ecosystem but still reach the Arctic, while others, such as the perfluorinated acids PFOS and PFOA, have no known environmental degradation pathways. Lifetimes of POPs in the environment span from days (in air) to decades and longer (in environmental media such as soil and sediment). Interactions with the climate, including potential re-emission from the ocean, occur over large geographic regions such as the Arctic and on timescales from decades to centuries.

Figure 2 draws attention to the fact that scientific aspects of the chemicals problem – in particular, those aspects that affect long timescales and cross spatial scales – are only imperfectly addressed by existing policy mechanisms. Policy mechanisms tend to focus on the process of controlling. From a policy perspective, controlling (shown in Figure 2 as a blue arrow) focuses on limiting the emission of pollutants at the source (for example, bans on production and best available techniques for emission control). This prevents them from entering the environment and subsequently spreading across time and space, and is critical for preventing new damage, but does little in the short-to-medium term to address the aspects of the chemicals problem that already affect the environment. Combining Figure 1 and Figure 2 suggests that policy efforts ought to focus more on transforming and exchanging functions, bringing aspects of the chemicals problem that already affect longer temporal and spatial scales back into the realm where they can be addressed by policies, which are implemented in a specific place and time (bottom left corner). Policies that focus on transforming could focus on, for example, converting pollutants to less toxic forms, or regulating not only primary emission but also secondary transformation products. For exchanging, mechanisms to prevent exposure could include more effective dietary advice or interventions, or controls on POPs in articles in commerce. Better understanding of the stocks and flows of POPs already in the environment could facilitate these efforts.

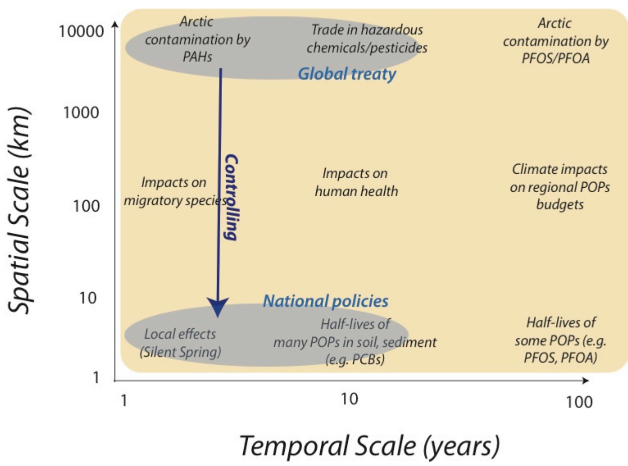

Fig. 2. Space-Time-Function illustration of chemicals in the Earth System

5 Integrating Engineering Systems and Sustainability Science: Ways Forward

The emerging fields of engineering systems and sustainability science have much substantively in common. They are both fields driven by the need to solve large-scale, real-world problems. Despite overlaps and similarities, however, these fields draw from very different disciplinary perspectives. A recent analysis of the evolution and structure of sustainability science based on a quantitative analysis of the literature (Bettencourt and Kaur, 2011) found that 32% of publications were from social sciences, 23% from biological sciences, and only 22% from engineering (chemical, mechanical, and civil). Of the engineering fields represented, soil science/quality, solar and wind power, wastewater, and coastal management research make up the majority (60%).

Viewing Earth as an engineering system raises the possibility that many of the methods and techniques of engineering systems as a field could be usefully applied to sustainability science, and vice versa. Historically, there has been little interaction between these two emerging fields. To facilitate future developments, several recommendations emerge. First, an increased focus on developing new approaches to system Earth from the engineering systems community would help to better characterize and understand system interactions. Application and extension of engineering systems methods to address Earth systems in their full natural and social complexity would contribute substantially to sustainability science as a field. Finally, further case studies could help illuminate the applications of new methods to the area of technology and policy.

Acknowledgments. We acknowledge support from the MIT Leading Technology and Policy program, the MIT Research Support Committee James H. Ferry Fund for Innovation in Research Education, and the U.S. National Science Foundation Atmospheric Chemistry Program under grant #1053648.

References

Anderson, S., Newell, R. (2004) Prospects for Carbon Capture and Storage Technologies. *Annual Review of Environment and Resources* 29, 109-142.

Bennett, D.H., McKone, T.E., Matthies, M., Kastenberg, W.E. (1998) General Formulation of Characteristic Travel Distance for Semivolatile Organic Chemicals in a Multimedia Environment. *Environmental Science & Technology* 32, 4023-4030.

Bettencourt, L.M.A., Kaur, J. (2011) Evolution and structure of sustainability science. *Proceedings of the National Academy of Sciences* 108, 19540-19545.

Bumpus, A.G., Liverman, D.M. (2008) Accumulation by Decarbonization and the Governance of Carbon Offsets. *Economic Geography* 84, 127-155.

Clark, W.C. (1985) Scales of Climate Impacts. *Climatic Change* 7, 5-27.

Clark, W.C. (2007) Sustainability science: a room of its own. *Proceedings of the National Academy of Sciences of the United States of America* 104, 1737-1738.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, k., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M. (1997) The value of the world's ecosystem services and natural capital. *Nature* 387, 253-260.

Crutzen, P.J. (2002) Geology of mankind. *Nature* 415, 23.

Cutcher-Gershenfeld, J., Field, F., Hall, R., Kirchain, R., Marks, D., Oye, K., Sussman, J., (2004) Sustainability as an organizing design principle for large-scale engineering systems, Engineering Systems Monograph. Massachusetts Institute of Technology, Cambridge, MA.

de Weck, O.L., Roos, D., Magee, C.L. (2011) *Engineering Systems: Meeting Human Needs in a Complex Technological World*. MIT Press, Cambridge, MA.

Ellerman, A.D., Buchner, B.K. (2008) Over-Allocation or Abatement? A Preliminary Analysis of the EU ETS Based on the 2005–06 Emissions Data. *Environmental and Resource Economics* 41, 267-287.

Evenson, R.E., Gollin, D. (2003) Assessing the impact of the green revolution, 1960 to 2000. *Science* 300, 758-762.

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D.M. (2006) Ethanol can contribute to energy and environmental goals. *Science* 311, 506-508.

Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grübler, A., Huntley, B., Jäger, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore, B., O'Riordan, T., Svedin, U. (2001) Sustainability Science. *Science* 292, 641-642.

Kerret, D., Gray, G.M. (2007) What do we learn from emissions reporting? Analytical considerations and comparison of pollutant release and transfer registers in the United States, Canada, England, and Australia. *Risk Anal* 27, 203-223.

Krueger, J. (1998) Prior Informed Consent and the Basel Convention: The Hazards of What Isn't Known. *The Journal of Environment & Development* 7, 115-137.

Lee, K.N. (1999) Appraising Adaptive Management. *Conservation Ecology* 3, 3.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J. (2008) Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America* 105, 1786-1793.

Lohmann, R., Jurado, E., Pilson, M.E.Q., Dachs, J. (2006) Oceanic deep water formation as a sink of persistent organic pollutants. *Geophysical Research Letters* 33.

Lubchenko, J. (1998) Entering the Century of the Environment: A New Social Contract for Science. *Science* 279, 491-497.

Magee, C.L., de Weck, O.L., (2004) Complex System Classification, Fourteenth Annual Symposium of the International Council on Systems Engineering (INCOSE), Toulouse, France.

Mooney, H.A., Cleland, E.E. (2001) The evolutionary impact of invasive species. *Proceedings of the National Academy of Sciences of the United States of America* 98, 5446-5451.

Ramaswami, A., Zimmerman, J.B., Mihelcic, J.R. (2007) Integrating Developed and Developing World Knowledge into Global Discussions and Strategies for Sustainability. 2. Economics and Governance. . *Environmental Science & Technology* 41, 3422-3430.

Richter, D.d.J. (2007) Humanity's Transformation of Earth's Soil: Pedology's New Frontier. *Soil Science* 172, 957-967 910.1097/ss.1090b1013e3181586bb3181587.

Schellnhuber, H.J. (2009) Tipping elements in the Earth System. *Proceedings of the National Academy of Sciences of the United States of America* 106, 20561-20563.

Scheringer, M., Fiedler, H., Suzuki, N., Holoubek, I., Zetzsch, C., Bergman, Å. (2006) Initiative for an international panel on chemical pollution (IPCP). *Environmental Science and Pollution Research* 13, 432-434.

Schwarzenbach, R.P., Gschwend, P.M., Imboden, D.M. (2003) *Environmental Organic Chemistry*. Wiley, Hoboken, NJ.

Seinfeld, J.H., Pandis, S.N. (2006) *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. Wiley Interscience, Hoboken, NJ.

Selin, H. (2010) *Global Governance of Hazardous Chemicals: Challenges of Multilevel Management*. MIT Press, Cambridge, MA.

Selin, H., Eckley, N. (2003) Science, Politics, and Persistent Organic Pollutants: The Role of Scientific Assessments in International Environmental Co-operation. *International Environmental Assessments: Politics, Law and Economics* 3, 17-42.

Selin, N.E., (2006) *From Regional to Global Information: Assessment of Persistent Organic Pollutants (POPs)*. in: Mitchell, R.B., Clark, W.C., Cash, D.W., Dickson, N.M. (Eds.), Global Environmental Assessments: Information, Institutions, and Influence. MIT Press, Cambridge, MA.

Selin, N.E. (2011) Science and strategies to reduce mercury risks: a critical review. *Journal of Environmental Monitoring* 13, 2389-2399.

Shaw, S.D., Brenner, D., Berger, M.L., Carpenter, D.O., Hong, C.-S., Kannan, K. (2006) PCBs, PCDD/Fs, and Organochlorine Pesticides in Farmed Atlantic Salmon from Maine, Eastern Canada and Norway, and Wild Salmon from Alaska. *Environmental Science & Technology* 40, 5347-5354.

Stokes, D.E. (1997) *Pasteur's quadrant: basic science and technological innovation*. Brookings, Washington, D.C.

Stommel, H. (1963) Varieties of Oceanographic Experience. *Science* 139, 572-576.

Trapp, S., Bomholz, L.M., Legind, C.N. (2008) Coupled mother-child model for bioaccumulation of POPs in nursing infants. *Environmental Pollution* 156, 90-98.

Vance, T.C., Doel, R.E. (2010) Graphical Methods and Cold War Scientific Practice: The Stommel Diagram's Intriguing Journey from the Physical to the Biological Environmental Sciences. *Historical Studies in the Natural Sciences* 40, 1-47.

Vitousek, P.M., Mooney, H.A., Lubchenko, J., Melillo, J. (1997) Human Domination of Earth's Ecosystems. *Science* 277, 494-499.

Wania, F., Mackay, D. (1996) Tracking the Distribution of Persistent Organic Pollutants. *Environmental Science & Technology* 20, 390A-396A.

Westley, F., Carpenter, S.R., Brock, W.A., Holling, C.S., Gunderson, L.H., (2002) *Why Systems of People and Nature Are Not Just Social and Ecological Systems*, in: Gunderson, L.H., Holling, C.S. (Eds.), Panarchy: Understanding Transformations in Systems of Humans and Nature. Island Press, Washington, DC.

Zalasiewicz, J., Williams, M., Smith, A., Barry, T.L., Coe, A.L., Bown, P.R., Brenchley, P., Cantrill, D., Gale, A., Gibbard, P., Gregory, F.J., Hounslow, M.W., Kerr, A.C., Pearson, P., Knox, R., Powell, J., Waters, C., Marshall, J., Oates, M., Rawson, P., Stone, P. (2008) Are we now living in the Anthropocene. *GSA Today* 18, 4.