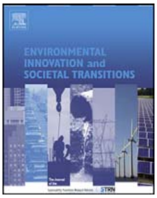
Environmental Innovation and Societal Transitions 1 (2011) 160–165

Contents lists available at ScienceDirect

Environmental Innovation and Societal Transitions

journal homepage: www.elsevier.com/locate/eist



Sustainable prosperity and societal transitions: Long-term modeling for anticipatory management

Matthias Ruth[a,*], Eugenia Kalnay[a], Ning Zeng[a], Rachel S. Franklin[b], Jorge Rivas[c], Fernando Miralles-Wilhelm[d]

[a] *University of Maryland, United States*
[b] *Brown University, United States*
[c] *University of Minnesota, United States*
[d] *Florida International University, United States*

ARTICLE INFO

Article history:
Received 4 November 2010
Received in revised form 24 February 2011
Accepted 14 March 2011

ABSTRACT

The coupled nature of human and earth system dynamics has become increasingly apparent as humanity's environmental footprint has increased. Yet, the methods and processes used to understand and guide those dynamics remain deficient in their treatment of that coupling. Lack of bi-directional coupling of human system dynamics with the dynamics of the larger environment within which humanity operates stymies the ability of researchers and policymakers to anticipate and limit the unintended consequences of technological change and help guide associated societal transitions. This paper lays out elements of a research agenda to ameliorate those deficiencies.

1. History as interrelated technological, social and environmental changes

Transitions play a fundamental conceptual role in our understanding of socio-economic change, whether we speak of the demographic, the epidemiologic, or the migration transition. Movement over time from one state of being to another has always been inseparably intertwined with technological innovation. Human history is replete with examples of these transitions leading to increases in prosperity followed by collapse (Diamond, 1994), and with examples of forecasts of impending economic and social stagnation and decay (Malthus, 1798). Generally, underlying this narrative of "transition"

---

* Corresponding author. Tel.: +1 301 405 6075; fax: +1 301 403 4675.
E-mail address: mruth1@umd.edu (M. Ruth).

doi:10.1016/j.eist.2011.03.004

has been the *leitmotif* of hope for further advancements (Simon and Kahn, 1984) and the call by eminent thinkers for the technological and institutional changes that are at our fingertips to influence the trajectory of progress and well-being (Ausubel and Sladovich, 1989; Ausubel, 1991). Examples range from carbon-neutral provision of energy to sequestration of greenhouse gases, all in efforts to power economic growth without disturbing the climate conditions under which we live.

The development of an increasingly globalized economy adds new urgency to humanity's efforts to anticipate the challenges ahead and the opportunities for further prosperity. Calamities that once were regional in nature, such as endemic diseases, economic boom and bust cycles, or local social and political conflicts, now can rapidly spread to unravel the fabric of previously far-flung places (Claessens and Forbes, 2001), but globalization can also help mobilize distant resources to address local challenges (Sachs, 2005). The uncertainty about possible outcomes of ever larger numbers of interactions among ever larger numbers of people, businesses and institutions, keeps increasing, and the prospects for true surprises keep rising (Funtowicz and Ravetz, 1993).

Technological innovations in the areas of energy, transport, agriculture and water management, for example, have long been seen as ways to increase prosperity and overcome environmental constraints on socioeconomic development. Yet, the ensuing economic and population growth, rebound effects, and emergence of unintended consequences have frequently run counter to the improvements promised by new technology (Ruth, 2007, 2009). Enhancing the prospects for long-term prosperity while minimizing the potential for surprise will require further innovations in problem solving concepts and in institutional design. Conceptual innovations must include advancements in data collection, analysis and modeling that take a comprehensive systems view of environmental, technological and socioeconomic changes, rather than focusing on isolated system components. As we illustrate below, the physical and life sciences are at the cusp of delivering essential insights into human impacts on earth system dynamics by drawing on a range of remote and *in situ* measurements and highly sophisticated computer models. In contrast, the social and behavioral sciences have not yet organized themselves in a similar fashion, or connected their theoretical and empirical knowledge in truly cross-disciplinary ways that can "zipper up" the insights on human with environmental system dynamics across regions and to global scales.

For the technological innovations to hold their promise, three kinds of institutional innovations must take place – one within the academic world, where the sciences are integrated to advance understanding of coupled human–earth system dynamics; a second, in which the sciences and modeling mutually inform, and are informed by societal needs; and a third, in which institutions guide investment and policy making on the basis of bi-directional human–earth system dynamics rather than with a narrow view towards direct, desired impacts. Collectively, these innovations will need to combine advancements in monitoring, modeling, information management, and communication in a deliberative decision making environment. The remainder of this paper lays out essential elements of such innovations.

2. Understanding coupled human–earth system dynamics

In efforts to tease apart the many interacting influences on environmental and human conditions, the natural and human systems have typically been studied in a one-way coupled fashion, i.e., one component as input, while the other responds. Examples of this one-way coupling approach include demographic projections used to predict demand for natural resources (water and energy), and natural disasters triggering human migration patterns. Mirroring this separation, diverse institutions were developed to collect data on and monitor, for example, environmental and demographic change with typically only *ad hoc* exchanges between them. In the real world, both the human and natural components of the earth system are fully coupled internally and with each other, meaning that bi-directional coupling exists, for example, between resources and population, between atmosphere and ocean, and between socioeconomic and biophysical systems.

Neglecting bi-directional couplings renders models unable to exhibit important real-world phenomena and thus reduces their usefulness as tools to explain and prepare for these phenomena. For example, the atmosphere and the ocean are coupled in both directions, and the important chaotic phenomenon of El Niño-Southern Oscillation (ENSO) is the result of an instability of the coupled ocean–atmosphere system (Cane et al., 1986; Zebiak and Cane, 1987). By contrast, until the late 1990s, atmospheric and ocean models used to be coupled in a “one-way” mode: the atmospheric models would be affected by the sea surface temperature (SST) but could not change it, and the ocean models would be driven by the atmospheric wind stress and surface fluxes, but could not change them. ENSO phenomena could not be predicted.

Similarly, explaining the rise and fall of civilizations cannot be done in isolation from changes in their environment. Perhaps the most notable example of tightly coupled human–environment dynamics is found on Easter Island where lush forest covers and fertile soils were the dominant conditions at the time of first settlement. Changes in technology, population, institutions and environmental quality begot each other, ultimately resulting in the demise of a society considered, at one point, rather advanced (Brander and Taylor, 1998; Erickson and Gowdy, 2000; Reuveny and Decker, 2000).

Guiding socioeconomic development towards sustainability will require increased focus on coupled dynamics, and on the data and tools needed to describe them. However, realistic coupled models are considerably harder to develop than one-way coupled models because there is much more freedom for the coupled model to drift away from reality. For example, with a one-way coupling, the atmosphere can respond to the ocean sea surface temperatures (SST) but it cannot change it, so that the SST anchors the atmosphere within realistic limits of temperature. In a two-way coupling, by contrast, the temperatures of the coupled atmosphere–ocean system have much more freedom to drift away. This requires more careful modeling in order to develop realistic solutions. At present, fully coupled climate models have been developed to the extent that they are now realistic, and there is general agreement among climate modelers that full coupling is essential in order to have a realistic climate system.

Advances in human system modeling have progressed significantly more slowly compared to their counterparts in climatology. Yet, it is the human driven processes that increasingly lie at the heart of global biogeochemical cycles and associated climate dynamics. Human systems now dominate the natural system, with, for example, the vast majority of large mammals being domesticated. Most of the land that can be cultivated has already been devoted to agriculture, and the production of grain has increased by 250% between 1950 and 1985, allowing the population to double during that period. This “green revolution” was made possible by the use of vast amounts of fossil fuels to fertilize, irrigate and mechanize agriculture. Humans now appropriate the bulk of net primary production (Vitousek et al., 1997) and have a heavy hand in virtually every major metal’s cycling (Nriagu, 1990). In fact, population growth is a primary driver of every environmental challenge that threatens sustainability: generation of greenhouse gases, other pollutants and toxic waste; depletion of resources, including water, oil, fisheries, and topsoil; resource wars and civil conflicts; malnutrition and world hunger; lack of resources for education and health care, especially in poor countries; best farmland converted to urban and suburban sprawl; waste disposal and need to find more landfill space; species extinction; and more.

With respect to population dynamics and characteristics, social scientists have developed a rich body of research seeking to explain, for example, migration and fertility behaviors at the local, regional, and global scales. In the context of environmental change, the importance of the fertility–mortality balance has long been understood, as it is a primary driver of population growth in much of the world. Researchers in environmental fields have also explored the link between changing age structures, growing urban populations and climate change (O’Neill et al., 2010). It is acknowledged fact that population characteristics – age, education, wealth – and not just raw size are important inputs to climate change (Jiang and Hardee, 2010; Franklin and Ruth, 2010). Arguably, though, there has been less work done to incorporate the wealth of research in the social sciences that seeks to understand *why* populations have a particular age structure, level of education, or a particular economic well-being, and *how* these may be constrained or fostered with changes in environmental conditions. Incorporating those insights from the social sciences into coupled models will represent a real challenge, but one that must be met.

Despite considerable efforts in the integrated assessment modeling community to link socioeconomic and biogeochemical dynamics with each other, coupling is weak and simplified at best, and the demographic components rarely interact bi-directionally with the rest of the model (for illustrations see, for example, Prinn et al., 1999; Sokolov et al., 2003; Webster et al., 2003; Kim et al., 2006; Bouwman et al., 2006; Riahia et al., 2007; EPRI, 2009). Even where coupling is a major focus of the research effort, simplistic economic decision-making – such as conditions for equilibrium on all relevant markets – are imposed, which in essence limit the normally time-lagged and nonlinear ripple effects of one system on the other as adjustments take place. Yet, the expressed intent of developing integrated assessment models has long been to help guide national and international policy-making in a world of imperfect foresight and imperfect markets. With a lack of bi-directionality in the models and jejune assumptions about human decision-making, many unintended consequences of investment and policy decisions cannot properly be captured.

3. Research needs

Starting from the premises that (a) physical laws place relevant constraints on the extent to which materials and energy can be used in a materially closed world (Georgescu-Roegen, 1971; Ruth, 1993), (b) increases in both population and affluence tend to drive the human enterprise closer to those limits (Daly, 1977), and (c) long-term prosperity is jeopardized if we remain ignorant of, and do not respond in accordance with the many important two-way relationships between and among human and natural systems, we see the need for a broad-based science and modeling initiative akin to the space programs launched in the 1960s or the mobilization of the climate community around climate change modeling in the 1980s. Important elements of this initiative will be:

3.1. *True coupling*

Following the inspirations of the Limits to Growth models (Meadows et al., 1972; Meadows, 2004), which were shown to have good agreement with what actually happened 30 years after the first study was completed (Turner, 2008), we see a need for a dynamic model with regional submodels. Such a model can be relatively simple to design and couple with the natural system. Building it on regional or country submodels will allow for consideration of the impact of government policies, migration, and disturbances such as HIV, as well as the regional vulnerabilities associated with sea level rise, erosion, etc.

3.2. *Open source*

Development of a coupled human–environment model serves the dual purpose of capturing important real-world dynamics and shaping the way in which we think and act about the long-term human–environment interactions at regional and global scales. To accomplish these goals will require drawing on an arsenal of submodels based on empirical, location and case-specific knowledge, and contributing to the suppliers of that knowledge in the research and practitioner communities. That cannot be done as an exercise of proprietary model development but will require free sharing and testing of data, models and model runs in an open source environment.

3.3. *Stakeholder involvement*

The coupled human–earth model will help generate a suite of scenarios of potential future human prosperity under a wide range of possible interventions into, and interferences with Earth system dynamics. Selection among alternative actions that move the human–earth system to desirable outcomes will inevitably be subject to the complexities of the policy process. Involving stakeholders from decision-making communities throughout the modeling process will be essential for successful communication about the model, its workings and the lessons it suggests. Communicating with stakeholders and involving them in the uses of the model in a controlled and carefully monitored fashion, will also be an important prerequisite to better capture decision making in the model itself. As decision makers learn from model behavior and conceive of alternative system intervention, modelers dealing with the human–earth system dynamics will be able to observe and experiment with behavioral change.

4. Anticipatory management for long-term prosperity

Since human activity has profound effects on the earth system, and since the earth system creates the constraints and effects within which the human system may prosper, we argue that human system regional/country models should be coupled with the earth system models to better simulate these effects, gain an improved understanding of the range of feedback and response dynamics of the coupled human–earth system and arrive at a quantitative tool that can be used for next-generation decision making and development of policies towards sustainability. Otherwise, the lack of coupling between the human and earth systems eliminates absolutely crucial feedbacks and will necessarily lead to “surprises” in the policy realm (Liu et al., 2010), many of which could have been anticipated. Of particular interest here will be explorations into societal transitions as environmental constraints become increasingly binding, and into technological and institutional innovations that may promise long-term prosperity.

While there will be, and has to be, diversity and plurality in the contributions to *Environmental Innovation and Societal Transitions,* we think that the research agenda laid out above may serve as one of the organizing themes for those contributions – both in content and in purpose. Empirical analysis, computer-based modeling, integrative science, and communication with stakeholders, all will be essential elements in efforts to identify transitions from the current reality of population and economic growth to sustainable development paths.

References

Ausubel, J.H., 1991. Does climate still matter? Nature 350 (April (25)), 649–652.

Ausubel, J.H., Sladovich, H.E. (Eds.), 1991. Technology and Environment, National Academy of Engineering. National Academy Press, Washington, DC, 1989.

Bouwman, A.F., Kram, T., Klein, K., Goldewijk (Eds.), 2006: Integrated Modeling of Global Environmental Change: An Overview of IMAGE 2.4. ISBN 9069601516. Available for free downloading at http://www.mnp.nl/bibliotheek/rapporten/500110002.pdf (228 pp).

Brander, J.A., Taylor, M.S., 1998. The simple economics of easter island: a Ricardo-Malthus model of renewable resource use. The American Economic Review 88, 119–138.

Cane, M.A., Zebiak, S.E., Dolan, S.C., 1986. Experimental forecasts of El Niño. Nature 321, 827–832.

Claessens, S., Forbes, K.J. (Eds.), 2001. International Financial Contagion. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Daly, H.E., 1977. Steady-State Economics. W.H. Freeman, San Francisco, CA.

Diamond, J., 1994. Ecological collapses of past civilizations. Proceedings of the American Philosophical Society 138 (September (3)), 363–370.

EPRI (Electric Power Research Institute), 2009: PRISM/MERGE Analyses: 2009 Update. Available at http://www.mydocs.epri.com/docs/public/000000000001019563.pdf.

Erickson, J.D., Gowdy, J.M., 2000. Resource use, institutions, and sustainablility: a tale of two Pacific islands. Land Economics 76, 345–354.

Franklin, R.S., Ruth, M., 2010. Growing up and cleaning up: the environmental Kuznets curve redux, Applied Geography, doi:10.1016/j.apgeog.2010.10.014.

Funtowicz, S.O., Ravetz, J.R., 1993. Science for the post-normal age. Futures 25 (September (7)), 739–755.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge, MA/London, England.

Jiang, L., Hardee, K., 2010. How do recent population trends matter to climate change? Population Research Policy Review, DOI 10.1007/s11113-010r-r9189-7.

Kim, S.H., Edmonds, J., Lurz, J., Smith, S., Wise, M., 2006. The object-oriented energy climate technology systems (ObjECTS) framework and hybrid modeling of transportation in the MiniCAM long-term, global integrated assessment Model. The Energy Journal, Special Issue: Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 63–91.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.W., 2010. Complexity of coupled human and natural systems. Science 317, 1513–1518.

Malthus, T.R., 1798. An essay on the principle of population, as it affects the future improvement of society: with remarks on the speculations of Mr. Godwin, M. Condorcet and other writers, Printed for J. Johnson, London.

Meadows, D.H., et al., 1972. The Limits to Growth. Universe Books, New York.

Meadows, D.H., Randers, J., Meadows, D.L., 2004. Limits to Growth: The 30-year Update. Chelsea Green Publishing Company, Post Mills, Vermont.

Nriagu, J.O., 1990. Global metal pollution: poisoning the biosphere? Environment: Science and Policy for Sustainable Development 32 (September (7)), 7–33.

O'Neill, B.C., Dalton, M., Fuchs, R., Jiang, L., Pachauri, S., Zigova, K., 2010. Global demographic trends and future carbon emissions. Proceedings of the National Academy of Sciences, Published online before print October 11, 2010, doi: 10.1073/pnas.1004581107.

Prinn, R., Jacoby, H., Sokolov, A., Wang, C., Xiao, X., Yang, Z., Eckaus, R., Stone, P., Ellerman, D., Melillo, J., Fitzmaurice, J., Kicklighter, D., Holian, G., Liu, Y., 1999. Integrated global system model for climate policy assessment: feedbacks and sensitivity studies. Climatic Change 41, 469–546.

Reuveny, R., Decker, C.S., 2000. Easter Island: historical anecdote or warning for the future? Ecological Economics 35, 271–287.

Riahia, K., Grübler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74, 887–935.

Ruth, M., 1993. Integrating Economics, Ecology and Thermodynamics. Kluwer Academic Publishers, Dordrecht, The Netherlands, 251 pp.

Ruth, M., 2007. Integrative environmental research and education. International Journal of Environmental Technology and Management 7 (5/6), 632–643.

Ruth, M., 2009. The nature of the beast and the beast in nature: broadening the perspective of technology. The Bulletin of Science, Technology and Society 29 (5), 374–382.

Sachs, J.D., 2005. The End of Poverty: Economic Possibilities for our Time. Penguin Group, New York.

Simon, J.L., Kahn, H. (Eds.), 1984. The Resourceful Earth. Basil Blackwell, New York, NY.

Sokolov, A., Forest, C.E., Stone, P.H., 2003. Comparing oceanic heat uptake in AOGCM transient climate change experiments. Journal of Climate 16, 1573–1582.

Turner, G., 2008. A Comparison of ‘The Limits to Growth’ with thirty years of reality. Published by Global Environmental Change 18, 397–411.

Vitousek, P.M., Mooney, H.A., Lubchenco, J. Melillo, J.M., 1997. Human domination of earth’s ecosystems. Science 277, (July) 5325, 494–499.

Webster, M.D., Forest, C., Reilly, J., Baliker, M., Kicklighter, D., Mayer, M., Prinn, R., Sarofim, M., Sokolov, A., Stone, P., Wang, C., 2003. Uncertainty analysis of climate change and policy response. Climatic Change 61 (3), 295–320.

Zebiak, S.E., Cane, M.A., 1987. A model El Niño/Southern oscillation. Monthly Weather Review 115, 2262–2278, L17.