GEOSCIENCES

Bidirectional coupling between the Earth and human systems is essential for modeling sustainability

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The remarkably fast and recent growth of the human system has introduced tremendous changes in both the natural and social systems of our planet. Humans have dramatically modified the Earth system and are playing an increasingly dominant role in altering its components (atmosphere, land, ocean, ecosystems, etc.) and processes (e.g. carbon cycle, nitrogen cycle and water cycle). For example, the rate of change of atmospheric concentrations of CO_2, CH_4, and N_2O increased by over 700, 1000, and 300 times (respectively) in the period after the Green Revolution when compared to pre-industrial rates (see Fig. 1). The corresponding increase in the rate of change for population is about 2000 times. Human consumption of natural resources, and the resulting pollution/emissions, is nearing the global limits for continued human habitability [1–3]. The biosphere is approaching planetary critical transitions [4] and currently there is no clear indication that global population and per capita resource use will stop growing. The total impact of these human-driven changes threatens to overwhelm natural systems and the many critical functions that the Earth system provides for humans. The Earth system in turn has significant impacts on the human system. Understanding the future of human sustainability therefore requires modeling that accurately captures the complex bidirectional interactions between these two systems.

Today's Integrated Assessment Models (IAMs) have made major progress in modeling many components of the socioeconomic system that impact the Earth system. However, there is a growing recognition that the Earth and human systems are coupled with complex interactions [5]. In this issue, a team of distinguished scientists argues that a bidirectional coupling approach is needed to capture the nonlinear dynamics and feedbacks in the coupled system that are missing from present approaches. Current Earth system models have been developed with the natural components bidirectionally coupled; however, the coupling with the human system, if it exists, is unidirectional (e.g. with prescribed scenarios or population projections estimated by the UN as external drivers without feedbacks). Therefore, the important effects of a changing Earth on humans, such as the societal and economic impacts of climate change and biodiversity loss, do not play any dynamic role in this unidirectional coupling framework. Without considering the existing feedbacks, tipping points, delays and nonlinearities, our understanding of the sustainability of the Earth–human coupled system will be incomplete and inadequate. As a result, crucial impacts on demographic and economic variables such as inequality, economic growth and migration are not included, and even the possibility of outcomes such as societal collapses could be missed [6]. These facts and sustainability challenges highlight the urgent need for the two-way coupled Earth and human system framework.

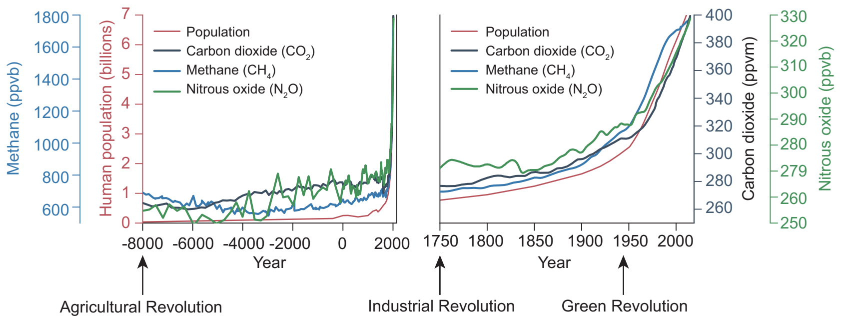

Figure 1. World population and atmospheric concentrations of major greenhouse gases since the beginning of the Agricultural Revolution about 10 000 years ago until the present (left), with a magnified timescale for the period after the beginning of the Industrial Revolution (right). Code, data, data sources, calculation of the rates of change and additional configurations of the figure are available at https://dx.doi.org/10.6084/m9.figshare.4029369.

This important new paper in this issue presents extensive evidence of the rapidly growing influence of the human system that dominates the natural systems on Earth in many different ways, such as human-appropriated net primary production, land cover change, disturbed biogeochemical and hydrological cycles, and emission of greenhouse gases from fossil fuels, all jeopardizing the future sustainability of humanity [7]. For example, the paper shows that, between 1950 and 2010, total human impact on the planet (as measured by Gross Domestic Product (GDP)) has grown about 4% per year on average, corresponding to a doubling of the impact every 17 years, with Population Growth and GDP per Capita Growth contributing about 1.7% and 2.2% to the total growth, respectively. The authors elaborate on the important roles of human system variables, in particular emphasizing economic inequality, population growth and per capita resource use, which are crucial to the evolution of the whole Earth–human system. These variables determine the total resource consumption, which, together with the carrying capacity (i.e. the total consumption that a given environment can support over the long term) of the Earth, will determine the sustainability of the system. Without incorporating bidirectional couplings, models will miss important dynamics in the real Earth–human system (e.g. the positive, negative and delayed feedbacks in the coupled system; see more in Motesharrei *et al.* [6] and Liu *et al.* [5]) that produce unexpected outcomes or require very different policy interventions. As the paper points out, current IAMs of climate change include sea-level rise, land degradation, regional changes in temperature and precipitation patterns, and some of the consequences for agriculture. However, the feedbacks that these significant impacts would have on the human system, such as geographic and economic displacement, forced migration, destruction of infrastructure and other effects on mortality, fertility and conflict, are not dynamically modeled. As examples of these feedbacks, the paper shows that anthropogenic climatic, environmental and land-use changes can severely affect human health and play a significant role in the spread of diseases; cause increased desertification and water scarcity; reduce snowpack, groundwater recharge, and freshwater quantity and quality; increase flood frequency and magnitude; cause sea-level rise and inundation of highly productive and densely populated coastal lowlands and cities; and can result in lower economic productivity, lower agricultural yields and the decline of national incomes. These changes can increase economic inequality, drive civil conflicts and trigger migration, which in turn could significantly increase future migration to more developed countries, resulting in an increase in total future resource use and emissions. Bidirectional coupling is required for models to include the effects of all of these feedbacks. Finally, the authors propose a groundbreaking modeling framework that includes bidirectional coupling between the Earth and human systems, suggesting methods such as dynamic modeling, input–output analysis, data collection, calibration and data assimilation for implementing such models. The proposed framework lays out an important direction for the future of Earth system modeling, and will have tremendous impacts on sustainable development and policy making. Major challenges still remain in building such a model, as discussed by Motesharrei *et al.* [7]. Constructing such coupled Earth–human system models requires multidisciplinary efforts by scientists of all related fields.

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