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Modeling sustainability: population, inequality, consumption, and bidirectional coupling of the Earth and Human Systems

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ABSTRACT

Over the last two centuries, the impact of the Human System has grown dramatically, becoming strongly dominant within the Earth System in many different ways. Consumption, inequality, and population have increased extremely fast, especially since about 1950, threatening to overwhelm the many critical functions and ecosystems of the Earth System. Changes in the Earth System, in turn, have important feedback effects on the Human System, with costly and potentially serious consequences. However, current models do not incorporate these critical feedbacks. We argue that in order to understand the dynamics of either system, Earth System Models must be coupled with Human System Models through bidirectional couplings representing the positive, negative, and delayed feedbacks that exist in the real systems. In particular, key Human System variables, such as demographics, inequality, economic growth, and migration, are not coupled with the Earth System but are instead driven by exogenous estimates, such as United Nations population projections. This makes current models likely to miss important feedbacks in the real Earth–Human system, especially those that may result in unexpected or counterintuitive outcomes, and thus requiring different policy interventions from current models. The importance and imminence of sustainability challenges, the dominant role of the Human System in the Earth System, and the essential roles the Earth System plays for the Human System, all call for collaboration of natural scientists, social scientists, and engineers in multidisciplinary research and modeling to develop coupled Earth–Human system models for devising effective science-based policies and measures to benefit current and future generations.

Keywords: Earth and Human System Models, population, migration, inequality, data assimilation, bidirectional couplings and feedbacks, sustainability

SIGNIFICANCE STATEMENT

The Human System has become strongly dominant within the Earth System in many different ways. However, in current models that explore the future of humanity and environment, and guide policy, key Human System variables, such as demographics, inequality, economic growth, and migration, are not coupled with the Earth System but are instead driven by exogenous estimates such as United Nations (UN) population projections. This makes the models likely to miss important feedbacks in the real Earth–Human system that may result in unexpected outcomes requiring very different policy interventions. The importance of humanity's sustainability challenges calls for collaboration of natural and social scientists to develop coupled Earth–Human system models for devising effective science-based policies and measures.

HIGHLIGHTS

(1) The Human System has become strongly dominant within the Earth System in many different ways.

(a) Consumption, inequality, and population have increased extremely fast, especially since ∼1950.

(b) The collective impact of these changes threatens to overwhelm the viability of natural systems and the many critical functions that the Earth System provides.

(2) Changes in the Earth System, in turn, have important feedback effects on the Human System, with costly and serious consequences.

(3) However, current models, such as the Integrated Assessment Models (IAMs), that explore the future of humanity and environment, and guide policy, do not incorporate these critical feedbacks.

(a) Key Human System variables, such as demographics, inequality, economic growth, and migration, are instead driven by exogenous projections, such as the UN population tables.

(b) Furthermore, such projections are shown to be unreliable.

(4) Unless models incorporate such two-way couplings, they are likely to miss important dynamics in the real Earth–Human system that may result in unexpected outcomes requiring very different policy interventions.

(5) Therefore, Earth System Models (ESMs) must be bidirectionally coupled with Human System Models.

(a) Critical challenges to sustainability call for a strong collaboration of both earth and social scientists to develop coupled Earth–Human System models for devising effective science-based policies and measures.

(b) We suggest using Dynamic Modeling, Input–Output (IO) models, and Data Assimilation to build and calibrate such coupled models.

DESCRIPTION OF SECTIONS

The First Section, entitled 'Dominance of the Human System within the Earth System', describes major changes in the relationship between the Earth System and the Human System, and key Human System factors driving these changes.

The Second Section, entitled 'Inequality, consumption, demographics, and other key Human System properties: projections vs. bidirectional coupling', provides examples of fundamental problems in the exogenous projections of key Human System factors used in current models.

The Third Section, entitled 'Human System threatens to overwhelm the Carrying Capacity and ecosystem services of Earth System', describes examples of changes in the Earth System that may impact the Human System seriously, as well as missing feedbacks from the Earth System onto the Human System.

The Fourth Section, entitled 'Bidirectional coupling of Human System and Earth System Models is needed. Proposed methodology: Dynamic Modeling, Input–Output models, Data Assimilation', argues for the need to bidirectionally couple both systems in order to model the future of either system more realistically, and proposes practical methods to implement this coupling.

DOMINANCE OF THE HUMAN SYSTEM WITHIN THE EARTH SYSTEM

Humans impact the Earth System by extracting resources and returning waste and pollution to the system, and simultaneously altering land cover, fragmenting ecosystems, and reducing biodiversity.[1]

The level of this impact is determined by extraction and pollution rates, which in turn, are determined by the total consumption rate. Total consumption equals population multiplied by average consumption per capita, both of which are recognized as primary drivers of human environmental impact.[2]

[1] Planet Earth has been the habitat of humans for hundreds of thousands of years. Human life depends on the resources provided by the Earth System: air from the Earth's atmosphere; water from the atmosphere and rivers, lakes, and aquifers; fruits from trees; meat and other products from animals; and over the past 10,000 years, land for agriculture, and metals and other minerals from the Earth's crust. Until about 200 years ago, we used renewable biomass as the major source of materials and energy, but over the course of the past two centuries, we have instead become heavily dependent on fossil fuels (coal, oil, and natural gas) and other minerals for both materials and energy. These nonrenewable resources made possible both of the revolutions which drove the the growth in consumption per capita and population: the Industrial Revolution and the Green Revolution. Our relationship with our planet is not limited to consuming its resources. Waste is an inevitable outcome of any production process; what is produced must return to the Earth System in some form. Waste water goes back to the streams, rivers, lakes, oceans, or into the ground; greenhouse and toxic gases go into the atmosphere, land, and oceans; and trash goes into landfills and almost everywhere else.

[2] Using gross domestic product (GDP) per capita as a rough measure of consumption per capita, the extent of the impact of the Human System on the Earth System can be estimated from the total population and the average consumption per capita. This can be also seen from the defining equation for GDP per capita, i.e., GDP per capita = GDP/Population. One may rewrite this equation as GDP = Population × GDP per capita. By taking variations, we get:

$$\frac{\delta \text{GDP}}{\text{GDP}} = \frac{\delta \text{Population}}{\text{Population}} + \frac{\delta \text{GDP per capita}}{\text{GDP per capita}}$$

This equation simply means that the relative change in the total GDP is comprised of two components, i.e., the relative changes in population and GDP per capita. A graphical demonstration of this decomposition can be seen in the inset of Fig. 1. Data from [229], with updates from the Maddison Project, 2013 (for the underlying methodology of the updates see [228]). Population data for the inset from [230].

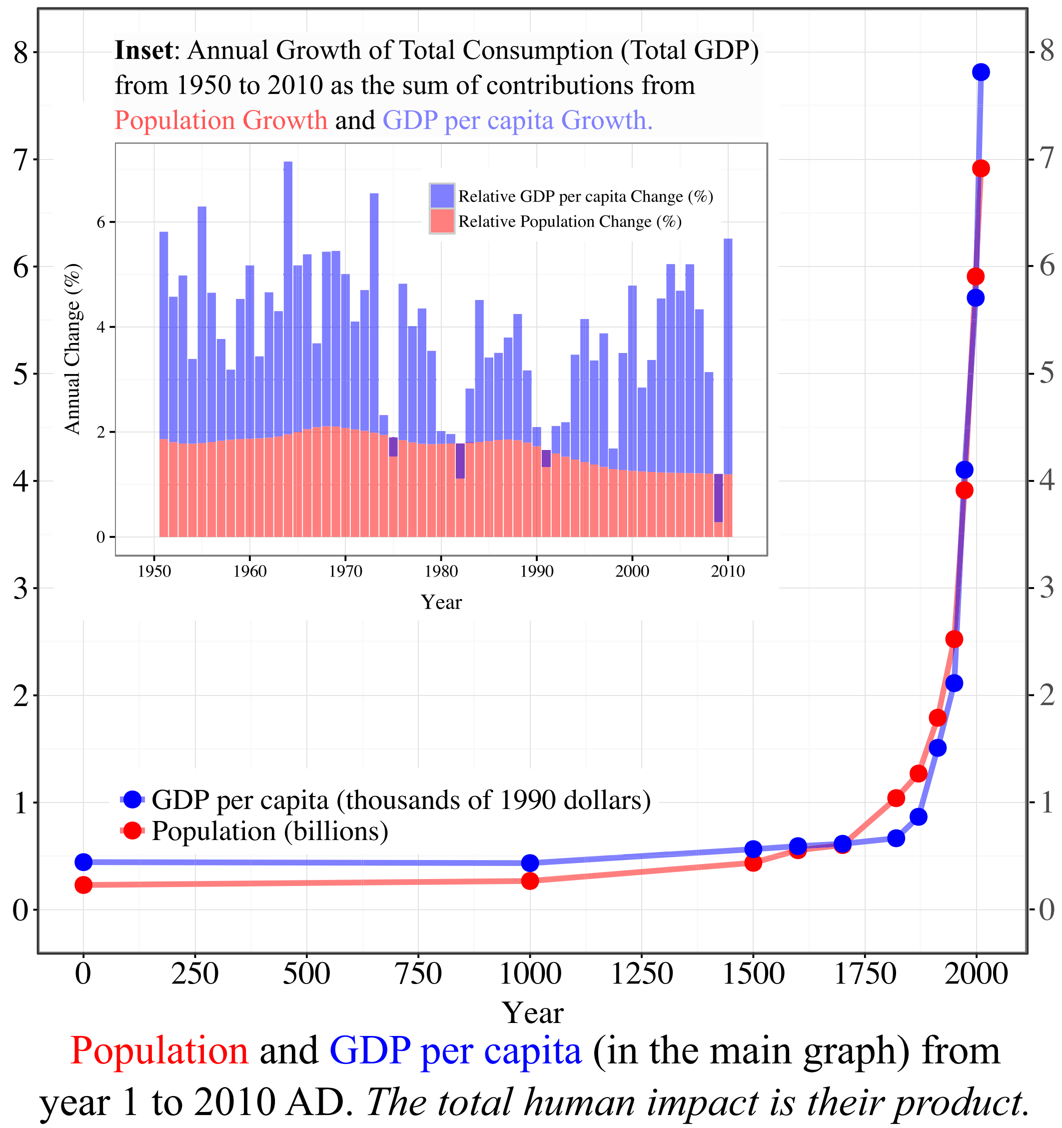

Figure 1. World population and GDP per capita from year 1 to 2010 AD. *The total human impact is their product.* The inset shows the relative annual change of each between 1950 and 2010 [228–230]. Their averages were 1.69% and 2.21%, respectively, out of a total of ∼4% (average annual change in GDP). Therefore, growth in population and consumption per capita have both played comparably important roles in the remarkable increase of human impact on planet Earth. This ∼4% total growth corresponds to doubling the total impact every ∼17 years. Note that the contribution from population growth has been relatively steady, while the contribution from the relative change in GDP per capita has been much more variable from year to year (even negative for some years). See Footnote 2 for a description of the mathematical formula used to generate the inset and sources of data.

The rapid expansion of the Human System has been a remarkably recent phenomenon (see Fig. 1). For over 90% of human existence, world population remained less than 5 million. After the Agricultural Revolution, it still took ∼10,000 years to reach 1 billion, around the year 1800. About a century later, the second billion was reached, around 1930. Thereafter, in less than a century, 5 billion more humans were added (within a single human lifetime). The peak in the *rate of growth* occurred in the 1960s, but because of the larger total population, the peak in *absolute growth* has persisted since the early 1990s [1]. To go from 5 to 6 billion took ∼12 years (1987–1999), and from 6 to 7 billion also took ∼12 years (1999–2011). The decline in the *rate* of growth over the past few decades has not significantly reduced the *absolute* number currently added every year, ∼80 million (e.g., 83 million in 2016), equivalent to the population of Germany [2,3].

A similar pattern holds for GDP per capita, but with the acceleration of growth occurring even more recently (see Fig. 1) and with the distribution of consumption becoming much more unequal. Thus, until the last century, population and GDP per capita were low enough that the Human System remained a relatively small component of the Earth System. However, both population and GDP per capita experienced explosive growth, especially after ∼1950, and the product of these two growths—total human impact—has grown from relatively small to dominant in the Earth System.

Contrary to popular belief, these trends still continue for both population and consumption per capita. The world is projected to add a billion people every 13–15 years for decades to come. The current UN medium estimate expects 11.2 billion people by 2100, while the high estimate is 16.6 billion.[3] Similarly, while the highest rates of growth of global per capita GDP took place in the 1960s, they are not projected to decline significantly from their current rates (so that estimates of annual global growth until 2040 range from 3.3% (IMF and IEA) to 3.8% (US EIA), implying a doubling time of ∼20 years).[4]

Two major factors enabled this demographic explosion. First, advances in public health, sanitation, and medicine significantly reduced mortality rates and lengthened average lifespan. Second, the rapid and large-scale exploitation of fossil fuels [4]—a vast stock of nonrenewable resources accumulated by Nature over hundreds of millions of years that are being drawn down in just a few centuries—and the invention of the Haber–Bosch process to use natural gas to produce nitrogen fertilizer [5,6] enabled increasingly higher levels of food and energy production. All these factors allowed for this fast growth of the Human System [7,8].[5]

Technological advances also allowed for the rapid increase in consumption per capita (see Fig. 1). This increase was made possible by a dramatic expansion in the scale of resource extraction, which, by providing a very large increase in the use of inputs, greatly increased production, consumption, throughput, and waste. During the fossil fuel era, per capita global primary energy and per capita global materials consumption have significantly increased over time. Despite tremendous advances in technological efficiencies, world energy use has increased for coal, oil, gas, and electricity since 1900, and global fossil fuel use per capita has continued to rise over the last few decades. There is no empirical evidence of reduction in use per capita, nor has there been an abandonment or long-term decline of one category through substitution by another. The same applies to global per capita use of materials for each of the major materials categories of minerals—industrial, construction, materials for ores, and materials derived from fossil energy carriers.[6]

The rapidly growing size and influence of the Human System has come to dominate the Earth System in many different ways [9–12]. Estimates of the global net primary production (of vegetation) appropriated by humans range as high as 55%, and the percentage impacted, not just appropriated, is much larger [13–23]. Human activity has also had a net negative effect on total global photosynthetic productivity since the most productive areas of land are directly in the path of urban sprawl [24]. Human use of biomass for food, feed, fiber, fuel, and materials has become a primary component of global biogeochemical cycles of carbon, nitrogen, phosphorous, and other nutrients. Land use for biomass production is one of the most important stressors on biodiversity, while total biomass use has continued to grow and demand is expected to continue growing over the next few decades [25]. Global food demand alone has been projected to double or more from 2000 to 2050 due to both rising population and rising incomes [26]. Most agriculturally usable land has already been converted to agriculture [27]. Most large mammals are now domesticated animals [28,29]. Soils worldwide are being eroded, fisheries exhausted, forests denuded, and aquifers drawn down, while desertification due to overgrazing, deforestation, and soil erosion is spreading [30–33]. Deforestation, in turn, affects local climate through evapotranspiration and albedo [34,35]. Since climate change is expected to make subtropical regions drier, desertification is expected to further increase,

[3] In fact, the UN's 2015 Population Revision has already raised the global total in 2100 by 360 million to 11.2 billion just from the last estimate published in 2013 [1].

[4] While there has been some reduction of the energy intensity and emissions intensity of economic growth in wealthy countries, one has to be cautious about extrapolating recent improvements, as small as they may be, because these improvements have been at least partly due to the outsourcing of energy-intensive sectors to poorer countries [122–130,231–233], and because there are basic physical limits to further efficiency improvements, especially in the use of water, energy, food, and other natural resources [113,114,234–236].

[5] For example, between 1950 and 1984, the production of grains increased by 250% due to the use of fossil fuels for fertilization, mechanization, irrigation, herbicides, and pesticides [237]. These technological advances, together with the development of new seed varieties, are referred to as the 'Green Revolution' that allowed global population to double in that period [238].

[6] Thus, while the rate of materials intensity of GDP growth has declined (very slowly: 2.5 kg/$ in 1950, 1.4 kg/$ in 2010), the per capita rate continues to increase. The only materials category whose per capita use has remained relatively stable is biomass [4,132], probably reflecting the physical limits of the planet's regenerating natural resources to continue to provide humans with ever-growing quantities of biomass [239,240]. (See [134] for a conceptual model of regenerating natural resources.)

especially due to bidirectional albedo–vegetation feedback [22].

At the same time, greenhouse gases (GHGs) from fossil fuels, together with land-use change, have become the major drivers of global climate change [10,36,37]. Atmospheric levels of carbon dioxide, methane, and nitrous oxide not only exceed pre-industrial concentrations by ∼40%, 150%, and 20%, respectively, they are now substantially above their maximum ranges of fluctuation over the past 800,000 years[7] [36] while total carbon dioxide emissions continue to grow at a rapid rate [38]. Arctic sea ice, Antarctic and Greenland ice sheets, global glacier mass, permafrost area, and Northern Hemisphere snow cover are all decreasing substantially, while ocean surface temperatures, sea level, and ocean acidification are rising [36]. Arctic sea ice is decreasing at an average rate of 3.0 ± 0.3 m^2 per metric ton of CO_2 emissions and at the current emissions rate of 35 gigaton per year could completely disappear by 2050 during Septembers [39]. The rate of ocean acidification, in particular, is currently estimated to be at least 100 times faster than at any other time in the last 20 million years [12].

The Human System dominates the global nitrogen cycle, having produced a 20% rise in nitrous oxide (N_2O) in the atmosphere, now the third largest contributor to global warming, and a tripling of ammonia (NH_3) in the atmosphere due to human activities [40]. In total, human processes produce more reactive nitrogen than all natural processes combined [12,41–45], altering the global nitrogen cycle so fundamentally that Canfield et al. [41] estimate the closest geological comparison occurred ∼2.5 billion years ago. Nitrogen and phosphorus fertilizer runoff, along with nitrogen oxides from fossil-fuel combustion (which is then deposited by rain over land and water) are causing widespread eutrophication in rivers, lakes, estuaries, and coastal oceans, and creating massive Dead Zones with little or no oxygen, which are increasing in number and size in coastal waters and oceans globally, killing large swaths of sea life and damaging or destroying fisheries. This may be compounded further by potentially dangerous positive feedbacks between hypoxia, ocean acidification, and rising sea temperatures [12,41,46–52].

Human activities also dominate many regional hydrological cycles [53–60], with more than half of all accessible surface freshwater being used by humans, to such an extent that some major rivers are being so excessively depleted that they sometimes no longer reach the sea, while some major inland fresh and salty water bodies, such as Lake Chad, Lake Urmia, Lake Poopó, and Aral Sea, are drying up. In many of the principal aquifers that support the world's agricultural regions and in most of the major aquifers in the world's arid and semi-arid zones, groundwater extraction is occurring at far greater rates than natural recharge. This includes aquifers in the US High Plains and Central Valley, the North China Plain, Australia's Canning Basin, the Northwest Sahara Aquifer System, the Guarani Aquifer in South America, and the aquifers beneath much of the Middle East and northwestern India [61–68]. Climate change can increase the frequency and severity of extreme weather events, such as hot and cold temperature extremes, heat waves, droughts, heavy precipitation, tropical cyclones, and storms [69–74]. In addition, more impervious surfaces together with other land cover changes increase runoff significantly, hence intensifying the adverse impacts of extreme hydrological events [75–77].

Many other socioeconomic trends and their impacts on the Earth System have accelerated synchronously since the 1950s with little sign of abatement [78,79]. For example, human processes play a major role in virtually every major metal cycle, leading to atmospheric and direct contamination of terrestrial and aquatic environments by trace-metal pollutants. Coal combustion is the major source of atmospheric Cr, Hg, Mn, Sb, Se, Sn, and Tl emissions, oil combustion of Ni and V, and gasoline combustion of Pb, while nonferrous metal production is the largest source of As, Cd, Cu, In, and Zn [80]. Surface mining has also become a dominant driver of land-use change and water pollution in certain regions of the world, where mountaintop removal, coal and tar sands exploitation, and other open pit mining methods strip land surfaces of forests and topsoils, produce vast quantities of toxic sludge and solid waste, and often fill valleys, rivers, and streams with the resulting waste and debris [81]. All of these trends can have an impact on other species, and while the exact causes are difficult to establish, current animal and plant species extinction rates are estimated to be at least 100 times the natural background rate [33,82–84]. Furthermore, ecosystems worldwide are experiencing escalating degradation and fragmentation, altering their health and provision of important ecosystem functions and services for humans and other species.[8]

[7] In some estimates, as much as 10–15 million years for carbon [241].

[8] Rates of deforestation and agricultural expansion have accelerated in recent years with extensive new infrastructure providing conduits for settlement, exploitation, and development. Even within the remaining habitat, fragmentation is causing rapid species loss or alteration, and is producing major impacts on biodiversity, regional hydrology, and global climate, in particular in tropical forests, which contain over half of Earth's biodiversity and are an important driver in the

Thus, the Human System has fundamentally impacted the Earth System in a multitude of ways. But as we will show, these impacts on the Earth System also feed back onto the Human System through various factors and variables: human health, fertility, well-being, population, consumption, economic growth, development, migration, and even producing societal conflict. Rather than incorporating these feedbacks, current models simply use independent projections of these Human System variables, often in a highly unreliable way.

INEQUALITY, CONSUMPTION, DEMOGRAPHICS, AND OTHER KEY HUMAN SYSTEM PROPERTIES: PROJECTIONS VS. BIDIRECTIONAL COUPLING

These large human impacts on the Earth System must be considered within the context of the large global economic inequality to realize that current levels of resource extraction and throughput only support societies at First World living standards for ∼17% of the world's current population [1]. The majority of the world's people live at what would be considered desperate poverty levels in developed countries, the average per capita material and energy use in developed countries is higher than in developing countries by a factor of 5 to 10 [25], and the developed countries are responsible for over three quarters of cumulative greenhouse gas emissions from 1850 to 2000 [85]. To place global resource-use inequality into perspective, it would require global resource use and waste production at least 2 to 5 times higher than it is now to bring the average levels of the ∼83% of the world's people living in developing countries up to the average levels of developed countries today [25]. The near-tripling in CO_2 emissions per capita in China from just 1990 to 2010 demonstrates the similar potential increases that could take place in the less developed world if this economic disparity is reduced [86]. Despite making China a focus of global concern because it became the single largest energy user and carbon emitter, China's 2010 per capita energy use (1.85 metric tons of oil equivalent, toe) was actually still below the world average (1.87 toe) [87,88]. The rest of the developing world, with the potential to reach similar levels of per capita emissions, has more than three times China's population. Furthermore, China's 2010 per capita carbon emissions (6.2 metric tons) were still only about a third of the US (17.6 metric tons) [89], indicating much more growth can still occur [86].

However, overall inequality in resource consumption and waste generation is greater than what these comparisons *between* countries demonstrate since resource consumption *within* countries is skewed towards higher income groups. In some countries, the Gini coefficient for carbon emissions (e.g., 0.49 in China and 0.58 in India [90]) is actually higher than the Gini coefficient for income (0.42 and 0.34 in 2010, respectively [91]). Rather than disaggregating resource consumption within countries, using national per capita GDP calculations and projections provides a distorted understanding of the distribution and characteristics of resource use and waste generation. Consumption patterns and associated per capita shares of resource use and pollution differ enormously, and using a consumption-based calculation rather than a national territorial production-based approach demonstrates even further the extent of global economic and environmental inequality: about 50% of the world's people live on less than $3 per day, 75% on less than $8.50, and 90% on less than $23 (US$ at current purchasing power parity). The top 10%, with 27.5 metric tons of GHG emissions per capita, produce almost as much total GHG emissions (46% of global total) as the bottom 90% combined (54%), with their per capita GHG emission of only 3.6 metric tons [87,90] (see Fig. 2).

Furthermore, even if per capita emissions stabilize or decline in the developed countries, population growth in these wealthy countries will remain a major driver of future increases in resource use and emissions. While some consider population growth a serious issue only in very poor countries, large population growth is still projected for some of the wealthiest countries today. For example, US, Canada, Switzerland, Sweden, Norway, Australia, and New Zealand are each projected to grow by about an additional 40%–80%.[9] Population growth in the developed countries is likely to be much higher than these UN estimates project

climate system. Ongoing worldwide habitat fragmentation, together with anthropogenic climate change and other human pressures, may severely degrade or destroy any remaining ecosystems and their wildlife [242–251]. For example, the Living Planet Index, which measures biodiversity based on 14,151 monitored populations of 3,706 vertebrate species, shows a staggering 58% decline in populations monitored between 1970 and 2012 [252]. Continuation of these trends could result in the loss of two-thirds of species populations by 2020 (only 4 years from now) compared to 1970 levels (i.e., in just half a century).

[9] The US, one of the highest resource use per capita countries in the world (e.g., with an energy consumption per capita 4 times that of China and 16 times that of India in 2010 [87]), is projected to grow in population by ∼50% from both natural increase and immigration, generating a very large increase in total resource use and waste generation for the US alone.

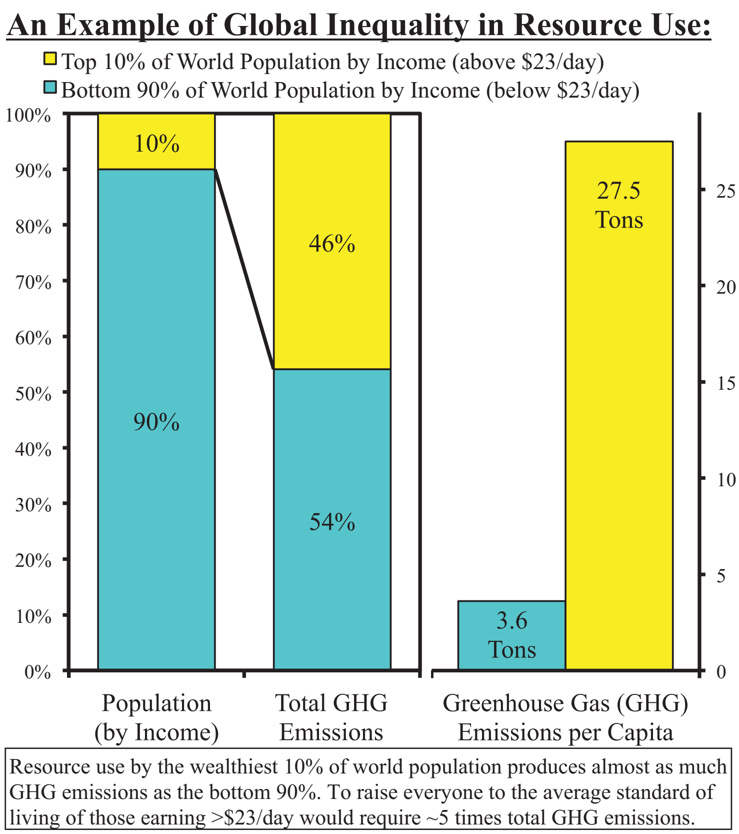

Figure 2. Global inequality in greenhouse gas emissions.

because these estimates include arbitrary projections of very low future immigration from less developed countries.[10] A model that uses these UN population projections incorporates these arbitrary and unrealistic assumptions into their projections, undermining its reliability. This is one reason why it is essential to project demographic variables endogenously within the models. One result of such unrealistically low projections of future migration to the developed countries is to produce lower estimates of future total emissions of the developed countries, which means the developed countries are not required to make as much effort today to lower their own emissions.[11]

Furthermore, the UN projections of a relatively stable population for the whole of the developed world depend on dramatic, and highly unlikely, declines projected in a handful of key countries. Japan, for example, must decline by ∼34%, Germany by ∼31%, and Russia by ∼30% for the projected stability in total developed country population to be born out.[12] In addition, countries often highlighted for their low birth rates, like Italy and Spain, are not projected to decline by even 1% for decades. Small increases in fertility and/or immigration could extend that period for decades longer. Even without those increases in fertility or immigration, the total population of developed countries is not projected by the UN to peak until about 2050, and trajectories beyond that are very difficult to predict given their high dependence on future policies.[13]

Since population is stabilizing in some countries, it is often thought that the human population explosion of the 20th century (growing by a factor of ∼4)

[10] For example, while Africa's population is projected to rise over 6-fold from 366 million in 1970 to 2.4 billion in 2050, the UN's projection of annual net emigration from Africa remains about constant until 2050, at ∼500,000, similar to the average from 1970 to 2000, thus the projected percentage emigrating declines sharply. (For comparison, between 1898 and 1914, ∼500,000 people emigrated each year just from Italy alone, when its population was only 30–35 million.) Then, from 2050 to 2100, the annual net emigration is arbitrarily projected to smoothly decline to zero, even as Africa's projected population continues rising to over 4 billion [3]. However, recent international migration has increased on average with global population [253] and net migration to the developed countries has increased steadily from 1960 to 2010 [3] and more explosively recently. Thus, the UN projection of emigration seems unrealistically low, both relative to its increasing population and in the context of a rapidly aging, and supposedly shrinking, population in the developed countries, as well as recent migration pattern alterations following conflicts and associated social disruptions. The United Nations High Commissioner on Refugees estimates that by the end of 2015, a total of 65.3 million people in the world were forcibly displaced, increasing at a rate of ∼34,000 people per day. There are 21.3 million refugees worldwide, with more than half from Afghanistan, Syria, and Somalia [254]. Yet, this figure only reflects refugees due to persecution and conflict but does not include refugees as a result of climate change, famines, and sea level rise. Net migration in 2015 to Germany alone was 1.1 million [255].The UN's 2012 projections of migration for other regions are similarly arbitrary and unrealistic. Net annual emigration from Latin America is projected to decline from nearly 1.2 million in 2000–2010 to ∼500,000 by 2050, and then decline to zero by 2100. Net annual immigration to Europe rose from 41,000 in 1960–1970 to almost 2 million in 2000–2010, and explosively today due to increasing social strife, and yet, the UN's projection for 2010–2050 is a continuous decline in net immigration down to only 900,000 by 2050, and then a decline to zero by 2100 [3]. Even the UN Population Division itself admits, 'We realize that this assumption is very unlikely to be realized but it is quite impossible to predict the levels of immigration or emigration within each country of the world for such a far horizon' [3].

[11] In order to limit the total increase in average global temperatures within the context of current climate change negotiations over carbon budgets, there is a maximum total amount of carbon that can be emitted globally, thus carbon emissions must be apportioned across countries and across time. Lower estimates of migration to developed countries means lower estimates of emissions in the future in developed countries, which means the developed countries are not required to make as much effort today to lower their own emissions [104].

[12] These dramatic declines appear highly unlikely given that countries like Japan and Germany have not yet declined by more than ∼1% [3], and already their governments have enacted a series of policies to encourage higher birth rates. In fact, there is evidence for the efficacy of various family policies in the recent fertility rebounds observed in several developed countries [97]. Similarly, Russia, which saw its fertility rate plunge after 1989 (reaching a low of 1.19 in 1999 from 2.13 in 1988), enacted pronatalist policies and liberalized immigration. The fertility rate has since rebounded, and the population decline reversed in 2009.

[13] Despite widespread talk of population decline, it is important to emphasize that the only countries in the world to have experienced any declines beyond ∼1% have all been associated with the special circumstances of the collapse of the former Soviet Bloc (and some microstates, such as a few island nations), and even in these cases, migration has played a major role in population changes. This is even true within Germany, where the only Länder (provinces) which have declined significantly in population are all from the former East Germany.

is over, and since rates of growth have been declining, family planning and population growth are no longer concerns. However, the UN projections of a stabilization in global population [3] are so far into the future (after 2100) that the projections are unreliable [8] and global stabilization itself is highly uncertain [92]. In fact, alternate projection methodologies suggest with much more certainty that stabilization is unlikely to occur [93]. Furthermore, even the UN projections are based on large assumed decreases in fertility rates in much of the world. If those projected decreases in fertility rates are off by only 0.5 births per woman (an error of less than 10% in many high-fertility countries), the date at which the world reaches 11 billion will occur five decades earlier and will raise the global total population by 2100 to nearly 17 billion and still rapidly growing [3]. Current projections should be understood in the context of past projections that have overestimated fertility declines.[14] Past mistaken projections reflect the use of highly questionable assumptions about fertility rate declines in developing countries [92] that tend to reproduce a 'natural' decline following the trajectory of more developed countries. Yet, the empirical record shows that reductions (or increases) in fertility rates reflect a complex range of sociodemographic, economic, and policy conditions [94–100]. If those conditions are not present, the projected declines will not necessarily occur, as can be seen in countries like Niger (7.4 births per woman in 1970, 7.6 in 2012) [101,102]. Needless to say, the use of demographic projections with overestimated fertility declines again produces underestimated projections of future resource use and emissions.

Even with these assumptions of large fertility declines in the projections, each additional billion humans added will not be spread evenly across the planet. The vast majority of the growth will be concentrated in countries that today continue to have very high rates of fertility (∼25 countries above 5, ∼45 above 4, and ∼65 above 3). These countries are also the lowest income countries in the world, with the lowest resource use per capita, which means that the majority of population growth is taking place precisely in regions with the highest potential for growth in resource use per capita over the coming decades [87], and the growth of the total impact is the product of the two. For example, the lowest-income continent, Africa, which had 230 million people in 1950 and over a billion in 2010 (a 4-fold increase in one lifetime) is currently on track to add another 3 billion in the next 85 years (another 4-fold increase in one lifetime). Nigeria, by itself, is projected to reach almost 1 billion people. These high projections already assume very large decreases in fertility rates from their current average levels of approximately 5 children/woman in Sub-Saharan Africa. (Without this projected decrease in fertility rates, Africa alone would add 16 billion rather than 3 billion more people by 2100 [3].) The UN medium range projections show that the developing world (not including China) will grow by an additional 2.4 billion people in just the next three and a half decades, and a total of an additional 4 billion by 2100. Due to these uneven population growth rates, ∼90% of the world's population will be living in today's less developed countries, with most of the growth in the poorest of these countries [3].[15]

Current projections of future resource use and greenhouse gas emissions used in the Intergovernmental Panel on Climate Change (IPCC) reports and Integrated Assessment Models (discussed further in the third Section) also depend heavily on a continuation of high levels of global economic inequality and poverty far into the future. Projections that global resource use and emissions will not rise very much due to rapid population growth in the poorest countries are based on the assumption that those countries will remain desperately poor by the standards of developed countries. (This assumption again provides the added benefit for today's wealthy countries that the wealthy countries have to make less effort today to reduce their own emissions. Given total global carbon emissions targets, projections of low economic growth in poor countries translate into less stringent carbon reduction requirements in wealthy countries [103,104].) However, China's recent rapid rise in emissions per capita shows this is a potential future path for the rest of the developing world. To argue otherwise requires assuming that today's developing countries will

[14] For example, the 1999 UN projections significantly overestimated the time it would take to add the next billion people [256]. Worse still, the 2015 estimate for the world's total population in 2100 [1] has gone up by over 2 billion just since the 2004 estimate [257]. Even the 2010 UN projections had to be revised upwards in 2012 because previous estimates of total fertility rates in a number of countries were too low, and in some of the poorest countries the level of fertility appears to have actually risen in recent years [3,258,259], and the 2012 estimates have again been revised upwards in 2015 [1]. To put all this in perspective, the 2004 estimates projected a peak in world population of 9.22 billion, but in the 2015 projection, 9.22 billion will be reached as early as 2041, and will still be followed by at least another six decades of growth.

[15] Poorer populations are expected to be more heavily impacted by climate change and other mounting environmental challenges despite having contributed much less to their causes [136,166,167,260]. International and internal migration is increasingly being seen as an important component of adaptation and resilience to climate change and a response to vulnerabilities from other environmental risks. Given the aging social structures in some parts of the world, policies that support increased migration could be important not only for environmental adaptation, but also for the realization of other socioeconomic and demographic goals. Thus, migration will help both the sending and receiving countries. Of course, given the scale of projected population growth, migration alone is unlikely to be able to balance the regional disparities.

remain in desperate poverty, and/or will adopt technologies that the developed countries themselves have yet to adopt. Real-world CO_2 emissions have tracked the high end of earlier emissions scenarios [105], and until the currently wealthy countries can produce a large decline in their own emissions per capita, it is dubious to project that emissions per capita in the less developed countries will not continue on a trajectory up to the levels of currently wealthy countries.[16]

As we will show, all of these points raise the critical issue of the accuracy and reliability of the assumptions underlying the projections of key Human System variables, such as inequality, population, fertility, health, per capita GDP, and emissions per capita. These are the central elements in many of the standard models used to explore the future of humanity and the environment, such as various IAMs used to guide policy, and models used by the IPCC whose output guides international negotiations on energy use and emissions. Common to these models is their deficiency in capturing dynamic bidirectional feedbacks between key variables of the Human System and the Earth System; instead, they simply use independent projections of Human System variables in Earth System Models.

HUMAN SYSTEM THREATENS TO OVERWHELM THE CARRYING CAPACITY AND ECOSYSTEM SERVICES OF EARTH SYSTEM

Economic theories that endorse limitless growth are based on a model of the economy that, in essence, does not account for the resource inputs and waste-absorption capacities of the environment, and the limitations of technological progress and resource substitutability. In other words, these theories essentially model the economy as a perpetual motion machine [106]. But in the real world, economic activity both consumes physical material and energy inputs and produces physical waste outputs. The Earth System performs the functions ('ecosystem services') of providing both the *sources* of these material and energy inputs to the human economy, as well as the *sinks* which absorb and process the pollution and waste outputs of the human economy. See Figs 3 and 4 [20,106–109]. Since the scale of the Human System has grown dramatically relative to the Earth System's capacity to provide these ecosystem services, the problems of *depletion* and *pollution* have grown dramatically.

Herman Daly has pointed out that the magnitude and growth rates of resource input and waste output are not sustainable: 'We are drawing down the stock of natural capital as if it was infinite' [110]. For example, the rapid consumption of fossil fuels is releasing vast stocks of carbon into the atmospheric and ocean sinks at a rate about a *million times faster* than Nature accumulated these carbon stocks.[17] Furthermore, while certain sectors of global society have benefited from the growth of the past 200 years, the environmental consequences are global in their impact, and the time scale of degradation of the resulting waste products (e.g., emissions, plastics, nuclear waste, etc.) is generally much longer than they took to produce or consume. Contrary to some claims within the field of Economics, physical laws do place real constraints on the way in which materials and energy drawn from the Earth System can be used and discharged by the Human System [111–114]. To be sustainable, human consumption and waste generation must remain at or below what can be renewed and processed by the Earth System.

It is often suggested that technological change will automatically solve humanity's environmental sustainability problems [115–117]. However, there are widespread misunderstandings about the effects of technological change on resource use. There are several types of technological changes, and these have differing effects on resource use. While some changes, such as in *efficiency* technologies, can increase resource-use efficiency, other changes, such as in *extraction* technologies and *consumption* technologies, raise the scale of resource extraction and per capita resource consumption. In addition, absent policy effects, even the increased

[16] The scientific community has urged limiting the global mean surface temperature increase relative to pre-industrial values to 2°C. The economic challenges of staying on a 2°C pathway are greater, the longer emission reductions are postponed [261]. Given the role that developed countries have played historically in the consumption of fossil fuels, and their much higher per capita carbon emissions today, it is imperative that the developed countries lead the way and establish a successful track record in achieving such reductions. Thus, it is positive that at the United Nations Framework Convention on Climate Change Conference of the Parties (COP21) in Paris in December 2015, governments crafted an international climate agreement indicating their commitments to emissions reduction for the near term (to 2025 or 2030). Most importantly, the US committed to reduce economy-wide GHG emissions below 2005 levels by 26%–28% in 2025, and the EU has committed to reduce 2030 GHG emissions relative to 1990 by 40% (excluding emissions from land-use changes). Assuming that the goals of the Intended Nationally Determined Contributions (INDCs) are fulfilled, the results in [262] and [261] show that a successful Paris agreement on near-term emissions reductions will be valuable in reducing the challenges of the dramatic long-term transformations required in the energy system to limit global warming to 2°C. The Paris framework will succeed even further if it enables development of subsequent pathways leading to the required additional global emissions reductions.

[17] As another example, millions of metric tons of plastic enter the oceans every year and accumulate throughout the world's oceans, especially in all subtropical gyres [263,264].

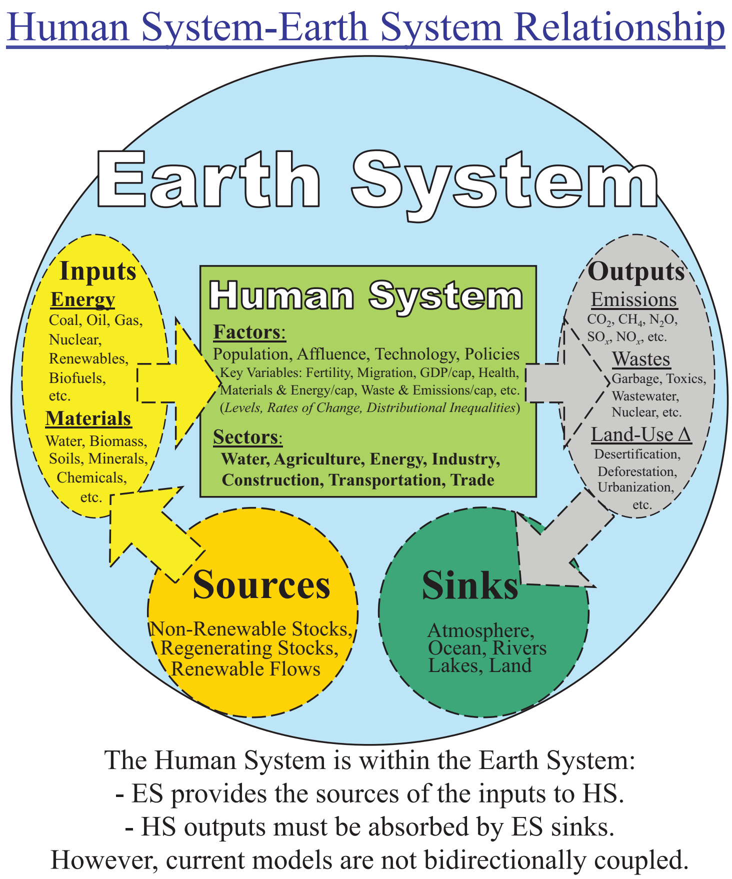

Figure 3. Relationship of the Human System within the Earth System, not separate from it (after [110]). The Earth System provides the sources of the inputs to, and the sinks that absorb the outputs of, the Human System.

technological efficiencies in resource use, are often compensated for by increases in consumption associated with the 'Rebound Effect' [118–121]. Furthermore, advances in *production* technologies that appear to be increases in productivity are instead very often due to greater energy and material inputs, accompanied by greater waste outputs. While the magnitude and even the sign of the effect of technological change on resource use varies greatly, the empirical record shows that the net effect has been a continued increase in global per capita resource use, waste generation, and emissions despite tremendous technological advances.

While per capita emissions of developed countries appear to be stabilizing when measured within the country of production, this is largely due to the shift in the location of energy-intensive manufacturing to developing countries, and estimates of developed countries' per capita emissions measured based on their consumption show that they continued to grow [122–130]. Even if today's industrialized societies can stabilize their resource use (at probably already unsustainable levels), large parts of the world are in the midst of this industrial transition and the associated technological regime shift from agrarian to industrial society that greatly increases per capita resource use and waste production [131,132].[18] For example, from just 1971 to 2010, total primary energy use per capita in Korea increased by a factor of 10, from 0.52 to 5.16 toe [88]. Therefore, technological advancement can add to the problems of global sustainability, rather than solve them. The question is not only whether technology can help solve environmental sustainability challenges, but also what policies and measures are required to develop the right technologies and adopt them in time. Technological advances could, and should, be part of the solutions for environmental and sustainability problems, for example, by transitioning to renewables, increasing use efficiency, and fostering behavioral changes to cut resource use and emissions, particularly in the high-resource-using countries. But these technological solutions do not just happen by themselves; they require policies based on scientific knowledge and evidence to guide and support their development and adoption.

An important concept for the scientific study of sustainability is Carrying Capacity (CC), the total consumption—determined by population, inequality, and per capita consumption—that the resources of a given environment can maintain over the long term [110,133].[19] Consumption of natural resources by a population beyond the rate that nature can replenish overshoots the Carrying Capacity of a given system and runs the risk of collapse. Collapses in population are common in natural systems

[18] The effect of technological change can be observed in the transition from agrarian to industrial society. This industrialization raised agricultural yields largely due to increasing inputs, thereby allowing rapid Human System expansion, but it also generated a societal regime shift that greatly increased per capita resource use and waste generation [131].

[19] One can generalize the definition of Carrying Capacity to any subsystem with different types of natural resources coupled with sociodemographic variables. For example, the subsystems for water, energy, and agriculture—each coupled bidirectionally to human sociodemographic variables and to each other—result in Water CC, Energy CC, and Agriculture CC. Water CC can be defined as the level of population that can be sustained at a particular per capita consumption and a given level of water sources and supply in the area under study. In general, this level depends on both human and natural factors. For example, Water CC is determined by the natural flow rate of water into and out of the area, precipitation and evaporation, withdrawal rate from water sources, dispensing technology, recycling capacity, etc. Moreover, Water, Energy, or Agriculture CC in a certain area can be imported from other regions to temporarily support a larger population and consumption [123,265,266]. Recent literature has emphasized the integrated nature of agricultural, energy, and water resources, and modeling the interactions of these subsystems is essential for studying the food–energy–water nexus [267–271]. In order to understand and model either Human or Earth Systems, we must model all these natural and human subsystems interactively and bidirectionally coupled.

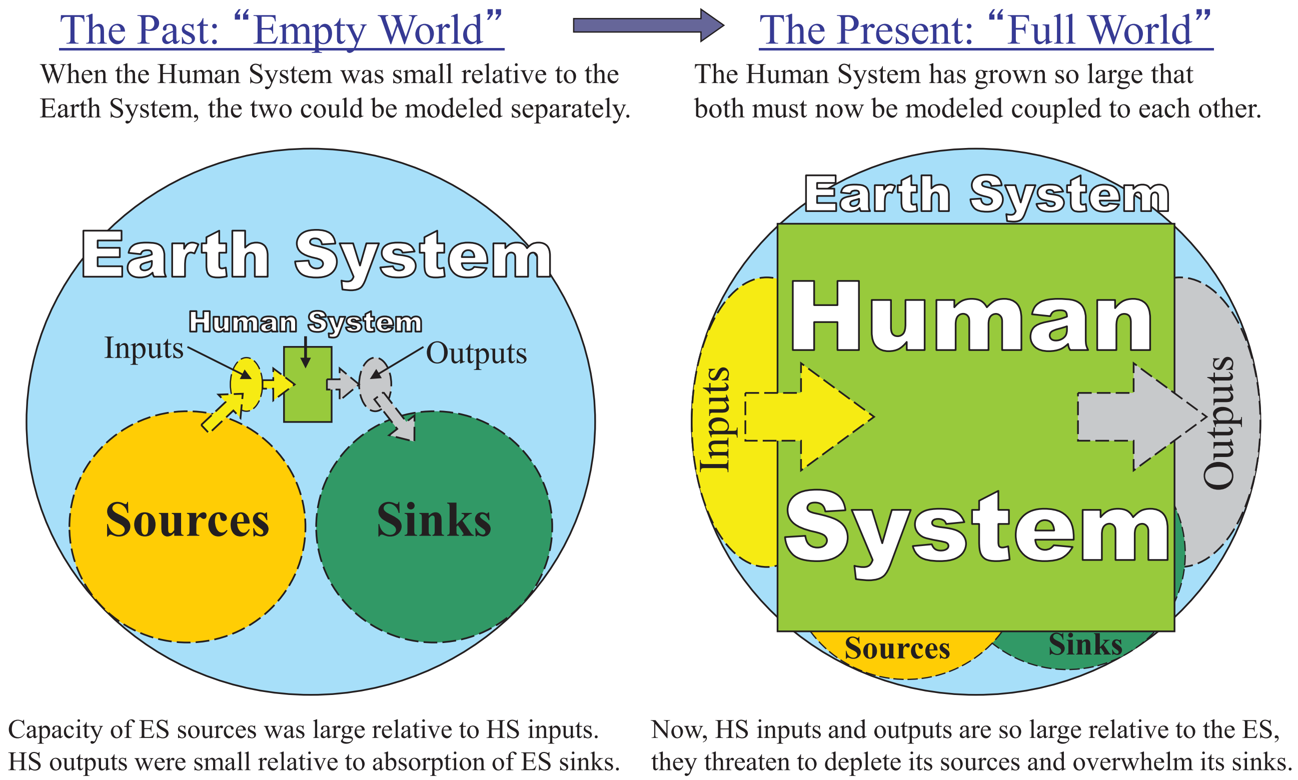

Figure 4. Growth of the Human System has changed its relationship with the Earth System and thus both must be modeled interactively to account for their feedback on each other.

and have occurred many times in human societies over the last 10,000 years.[20]

To study key mechanisms behind such collapses, Motesharrei et al. [134] developed a two-way coupled Human and Nature Dynamic model, by adding accumulated wealth and economic inequality to a predator–prey model of human–nature interaction. The model shows that both economic inequality and resource overdepletion can lead to collapse, in agreement with the historical record. Experiments presented in that paper for different kinds of societies show that as long as total consumption does not overshoot the CC by too much, it is possible to converge to a sustainable level. However, if the overshoot is too large, a collapse becomes difficult to avoid (see Fig. 5).[21] Modern society has been able to grow far beyond Earth's CC by using nonrenewable resources such as fossil fuels and fossil water. However, results from the model show that an unsustainable scenario can be made sustainable by reducing per capita depletion rates, reducing inequality to decrease excessive consumption by the wealthiest, and reducing birth rates to stabilize the population [134]. The key question is whether these changes can be made in time.

Current models of climate change include sea level rise, land degradation, regional changes in temperature and precipitation patterns, and some consequences for agriculture, but without modeling the feedbacks that these significant impacts would have on the Human System, such as geographic and economic displacement, forced migration, destruction of infrastructure, increased economic inequality, nutritional sustenance, fertility, mortality, conflicts, and spread of diseases or other human health consequences [135,136].

For example, nearly all features of the hydrologic system are now impacted by the Human System [60] with important feedbacks onto humans, e.g., snowpack decline due to climate change [53] reduces water availability; agricultural processes further affect water availability and water quality [54]; and land-use changes can reduce

[20] A recent study focusing on the many collapses that took place in Neolithic Europe concluded that endogenous causes, i.e., overrunning CC and the associated social stresses, have been the root cause of these collapses [214,272].

[21] Collapses could also happen due to rapid decline of CC as a result of environmental degradation. Droughts and climate change can decrease natural capacities and regeneration rates, which in turn lead to a decline of CC. (Motesharrei et al. [134] describe how to model these factors for a generic system, termed Nature Capacity and Regeneration Rate, and how they determine CC.) The resulting gap between total consumption and CC can lead to conflicts and the ensuing collapses. For example, see recent literature that shows the impacts of climate change on conflicts [159–161], a potential precursor to collapses.

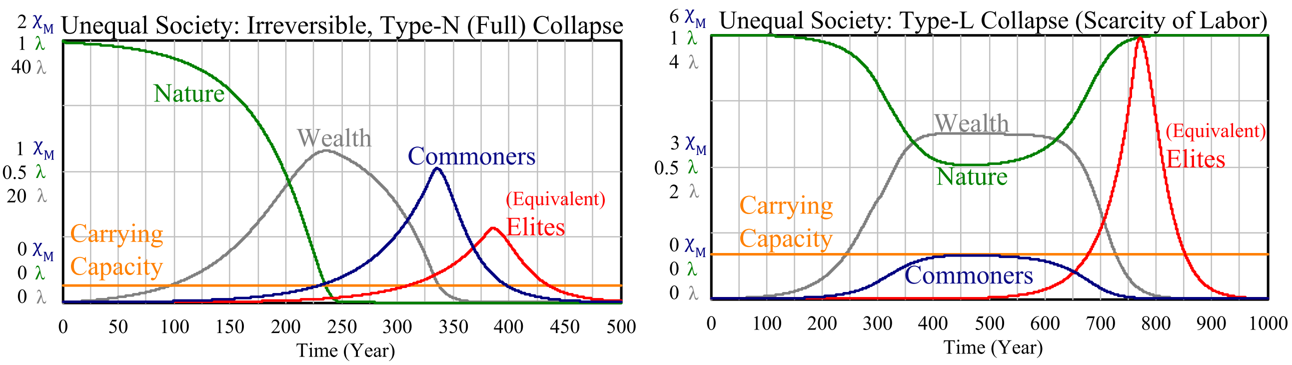

Figure 5. Example results from [134]. (Left panel) A type-N (Nature) collapse due to both overdepletion of Nature and inequality. (Right panel) A type-L (Labor) collapse: after an apparent equilibrium, population collapses due to overexploitation of Labor, although Nature eventually recovers.

groundwater recharge [77]. Thus many populations face both reduced water availability and increased flood frequency and magnitude [76]. Furthermore, chemicals used in hydraulic fracturing, which involves cracking shale rock deep underground to extract oil and gas, can contaminate groundwater resources [137–139]. In addition, the injection of wastewater from oil and gas operations for disposal into deep underground wells is also altering the stresses of geologic faults, unleashing earthquakes [140].[22] Increases in the frequency and magnitude of extreme weather events can impact agriculture and ecosystems [71,141].

Changes in the structure and functions of the ecosystem can also pose important threats to human health in many different ways [142]. Climate, climatic events (e.g., El Niño), and environmental variables (e.g., water temperature and salinity) can play a fundamental role in the spread of diseases [143–146]. A recent report by the US Global Change Research Program illustrates how climate change could affect human health through various processes and variables such as temperature-related death and illness, air quality, extreme events, vector-borne diseases, water-related illness, food safety and nutrition, and mental health and well-being [147].[23] Environmental catastrophes can result in the decline of national incomes for a few decades [148], and higher temperatures can severely affect human health [149] and reduce economic productivity [150]. This effect is in addition to the well-established reduction in agricultural yields due to higher temperatures [151–156]. Climate could also be a strong driver of civil conflicts [157–161]. Environmental change is also a known trigger of human migration [162–164]. These, in turn, will significantly increase the unrealistically small future migration projections described in the second Section of this paper. In fact, climate change alone could affect migration considerably through the consequences of warming and drying, such as reduced agricultural potential, increased desertification and water scarcity, and other weakened ecosystem services, as well as through sea level rise damaging and permanently inundating highly productive and densely populated coastal lowlands and cities [165–168]. Furthermore, the impacted economic activities and migration could then feed back on human health [169]. Bidirectional coupling is required to include the effects of all of these feedbacks.

[22] For example, 'Until 2008 not a single earthquake had ever been recorded by the U.S. Geological Survey from the Dallas-Fort Worth (DFW) area...Since then, close to 200 have shaken the cities and their immediate suburbs. Statewide, Texas is experiencing a sixfold increase in earthquakes over historical levels. Oklahoma has seen a 160-fold spike in quakes...In 2014 the state's earthquake rate surpassed California's'. [273].

[23] The USGCRP report states that 'Current and future climate impacts expose more people in more places to public health threats...Almost all of these threats are expected to worsen with continued climate change'.

BIDIRECTIONAL COUPLING OF HUMAN SYSTEM AND EARTH SYSTEM MODELS IS NEEDED. PROPOSED METHODOLOGY: DYNAMIC MODELING, INPUT–OUTPUT MODELS, DATA ASSIMILATION

Coupled systems can reveal new and complex patterns and processes not evident when studied separately. Unlike systems with only unidirectional couplings (or systems that just input data from extrapolated or assumed projections), systems with bidirectional feedbacks often produce nonlinear dynamics that can result in counterintuitive or unexpected outcomes [170]. Nonlinear systems often feature important dynamics which would be missed if bidirectional interactions between subsystems are not modeled. These models also may call for very different measures and policy interventions for sustainable development than those suggested by models based on exogenous forecasts of key variables.

The need for bidirectional coupling can be seen from the historical evolution of Earth System modeling. In the 1960s, atmospheric scientists developed the first mathematical models to understand the dynamics of the Earth's climate, starting with atmospheric models coupled to simple surface models (e.g., [171]). Over the following decades, new components such as ocean, land, sea-ice, clouds, vegetation, carbon, and other chemical constituents were added to make Earth System Models more physically complete. These couplings needed to be bidirectional in order to include feedbacks [171]. The importance of accounting for bidirectional feedbacks is shown by the phenomenon of El Niño-Southern Oscillation (ENSO), which results from the coupled dynamics of the ocean–atmosphere subsystems. Until the 1980s, atmospheric and ocean models were unidirectionally coupled (in a simple, 'one-way' mode): the atmospheric models were affected by sea surface temperatures (SST) but could not change them, and ocean models were driven by atmospheric wind stress and surface heat fluxes, but could not change them. Such unidirectional coupling could not represent the positive, negative, and delayed feedbacks occurring in nature that produce ENSO episodes. Zebiak and Cane [172] developed the first prototype of a bidirectional coupled ocean–atmosphere model. This model, for the first time, allowed prediction of El Niño several seasons in advance [173]. Similarly, improving the modeling of droughts requires bidirectional coupling of the atmosphere and land submodels (see, for example, [174]). Most current climate models have since switched to fully coupled atmosphere–ocean–land–ice submodels. This example shows that we can miss very important possible outcomes if the model fails to consider bidirectional feedbacks between different coupled components of systems that the model represent. Since the Human System has become dominant, it is essential to couple the Earth and Human Systems models bidirectionally in order to simulate their positive and negative feedbacks, better reflecting interactions in the real world.[24]

This coupling process has taken place to a certain extent, but the coupling does not include bidirectional feedbacks between the Human and Earth Systems. Energy and Agriculture sectors have been added to ESMs creating comprehensive Integrated Assessment Models. There are now several important, advanced IAMs, including MIT's IGSM, US DOE's GCAM, IIASA's MESSAGE, the Netherlands EAA's IMAGE, etc[25] [175–180]. However, in the IAMs, many of which are used in producing the IPCC reports, population levels are obtained from a demographic projection like the UN's population projections discussed in the first and second Sections, which do not include, for example, impacts that climate change may have on the Human System [181].

In today's IAMs, tables of projected demographic and socioeconomic variables determine changes in resource use and pollution/emission levels, which in turn can determine Earth System variables such as atmospheric temperature. However, changes in resource levels, pollution, temperature, precipitation, etc. estimated by the IAMs cannot, in turn, impact levels of these Human System variables and properties because they are exogenous to the IAMs. This is true even for the scenarios of the IPCC, which are constructed without full dynamic coupling between the human and natural systems. Although there are certain IAMs that include some couplings within human subsystems, critical feedbacks from natural systems onto demographic, economic, and human health variables are missing, so that the coupling

[24] Such interactions take place not just at a global scale but also at the ecosystem and local habitat scales. Ecosystems at the regional and local scales provide critical habitat for wildlife species, thus preserving biodiversity, and are also an essential source of food, fiber, and fuel for humans, and forage for livestock. Ecosystem health, composition, function, and services are strongly affected by both human activities and environmental changes. Humans have fundamentally altered land cover through diverse use of terrestrial ecosystems at the local scale, which then impact systems at the global scale. Additional changes have taken place as a result of climate change and variability [274]. Furthermore, human pressures are projected to have additional repercussions for species survival, biodiversity, and the sustainability of ecosystems, and in turn feedback on humans' food security and economic development [141]. Thus, a key challenge to manage change and improve the resilience of terrestrial ecosystems is to understand the role that different human and environmental forces have on them, so that strategies that target the actual drivers and feedbacks of coupled components of change can be developed and implemented. Understanding how terrestrial ecosystems function, how they change, and what limits their performance is critically important to determine their Carrying Capacity for accommodating human needs as well as serving as a viable habitat for other species, especially in light of anticipated increase in global population and resource consumption for the rest of this century and beyond. Biodiversity and ecosystem services in forests, farmlands, grazing lands, and urban landscapes are dominated by complex interactions between ecological processes and human activities. In order to understand such complexity at different scales and the underlying factors affecting them, an integrated Human–Earth systems science approach that couples both societal and ecological systems is needed. Humans and their activities are as important to the changing composition and function of the Earth system as the environmental conditions and their natural variability. Thus, coupled models are needed to meet the challenges of overcoming mismatches between the social and ecological systems and to establish new pathways toward 'development without destruction' [242–248,250,251].

[25] MIT: Massachusetts Institute of Technology; IGSM: Integrated Global System Modeling framework; US DOE: United States Department of Energy; GCAM: Global Change Assessment Model; IIASA: International Institute for Applied Systems Analysis; MESSAGE: Model for Energy Supply Systems And their General Environmental impact; EAA: Environmental Assessment Agency; IMAGE: Integrated Modelling of Global Environmental Change.

between human subsystems and the Earth System in most current modeling is unidirectional, whereas in reality, this coupling is bidirectional [181].

Without including such coupled factors, the independent projections of population levels, economic growth, and carbon emissions could be based on inconsistent or contradictory assumptions, and hence could be inherently incorrect. For example, the UN's population projections assume fertility declines in today's lowest-income countries that follow trajectories established by higher-income countries. However, the economic growth projections and, therefore, per capita carbon emission projections, assume today's poorest countries will not grow close to anywhere near the level of today's wealthy countries. The 45 lowest income countries are projected to grow to ~$6,500 GDP per capita by 2100 [104] but the average GDP per capita of today's high-income countries is ~$45,000. Rather than relying on projections, the demographic component of any coupled model must include the factors that contributed to the demographic transition in other countries, such as education, family planning, health care, and other government policies and programs [98,182–184].

Projections of key variables in a realistic model should not be based on mechanistic temporal extrapolations of those variables but rather on the intrinsic internal dynamics of the system. Specifically, key parameters of the Human System, such as fertility, health, migration, economic inequality, unemployment, GDP per capita, resource use per capita, and emissions per capita, must depend on the dynamic variables of the Human–Earth coupled system.[26] Not including these feedbacks would be like trying to make El Niño predictions using dynamic atmospheric models but with sea surface temperatures as an external input based on future projections independently produced (e.g., by the UN) without feedbacks.

To address the above issues, the development of coupled global Human–Earth System frameworks that capture and represent the interactive dynamics of the key subsystems of the coupled human–nature system with two-way feedbacks are urgently needed. The global Human–Earth System framework we propose, and represent schematically in Fig. 6, combines not only data collection, analysis techniques, and Dynamic Modeling, but also Data Assimilation, to bidirectionally couple an ESM containing subsystems for Global Atmosphere, Land (including both Land–Vegetation and Land-Use models) and Ocean and Ice, to a Human System Model with subsystems for Population Demographics, Water, Energy, Agriculture, Industry, Construction, and Transportation. The Demographics subsystem includes health and public policy factors that influence key variables such as fertility, disease, mortality, and immigration rates, while the Water, Energy, Agriculture, Industry, Construction, and Transportation subsystems include cross-national input–output modeling to provide the consumption-based resource-input and waste-output 'footprint' accounting analyses missing from the territorial-based methods.[27]

The need for global Earth System frameworks coupled to population drivers has been recommended since the 1980s, in the pioneering report by the Earth System Sciences Committee of the NASA Advisory Council, chaired by Francis P. Bretherton [185]. While Earth System components and

[26] Furthermore, the use of GDP as a key measure and determinant in these future projections is itself highly problematic, because it is a very weak measure of human well-being, economic growth, or societal prosperity [275]. GDP neither accounts for the value of natural capital nor human capital, ignores income and wealth inequality, neglects both positive and negative externalities, and only captures social costs and environmental impacts to the extent that prices incorporate them. Any economic activity, whether deleterious or not, adds to GDP as long as it has a price. For example, labor and resources spent to repair or replace loss due to conflicts or environmental damages are counted as if they add to—rather than subtract from—total output. Alternative measures, such as the Genuine Progress Indicator, the Sustainable Society Indicator, the Human Development Index, and the Better Life Index of the Organization for Economic Co-operation and Development, have been developed [276–278]. These measures show that, especially since the 1970s, the large increases in GDP in the developed countries have not been matched by increases in human well-being. Integrated and coupled Human–Earth system models will allow for the development of much more accurate and realistic measures of the actual productivity of economic activity and its costs and benefits for human well-being. Such measures will allow for the valuation of both natural and human capital and for defining and developing sustainability metrics that are inclusive of the wealth of natural and human capital. They will also bring together the current disparate debates on environment/climate, economics, demographics, policies, and measures to put the Human–Earth System on a more sustainable path for current and future generations.

[27] Input–Output analysis can account for the flows of resource inputs, intermediate and finished goods and services, and waste outputs along the production chain [279,280]. By accounting for the impacts of the full upstream supply chain, IO analysis has been used in life-cycle analysis [281] and for linking local consumption to global impacts along global supply chains [122,127,282,283]. IO models can be extended with environmental parameters to assess different environmental impacts from production and consumption activities, including water consumption [123,284,285], water pollution [285,286], carbon dioxide emissions [287–289], land-use and land-cover change [130,290,291], and biodiversity [283]). Such models have been developed and applied at various spatial and temporal scales. Since emissions embodied in trade have been growing rapidly, resulting in an increasing divergence between territorial-based and consumption-based emissions, territorial measures alone cannot provide a comprehensive and accurate analysis of the factors driving emissions nor the effectiveness of reduction efforts [292]. IO models can provide these consumption-based calculations and have been employed to identify and quantify key drivers for emissions and energy consumption (such as population growth, changes of consumption patterns, and technical progress [288,293,294]) as well as the environmental impacts of social factors (such as urbanization and migration) reflecting consumption patterns of different categories of households with high spatial detail [282,295]. IO analysis can also be used for simulating potential future states of the economy and the environment (e.g., [296]), through dynamically updating technological change and final demand, or employing recursive dynamics to explore explicit scenarios of change.

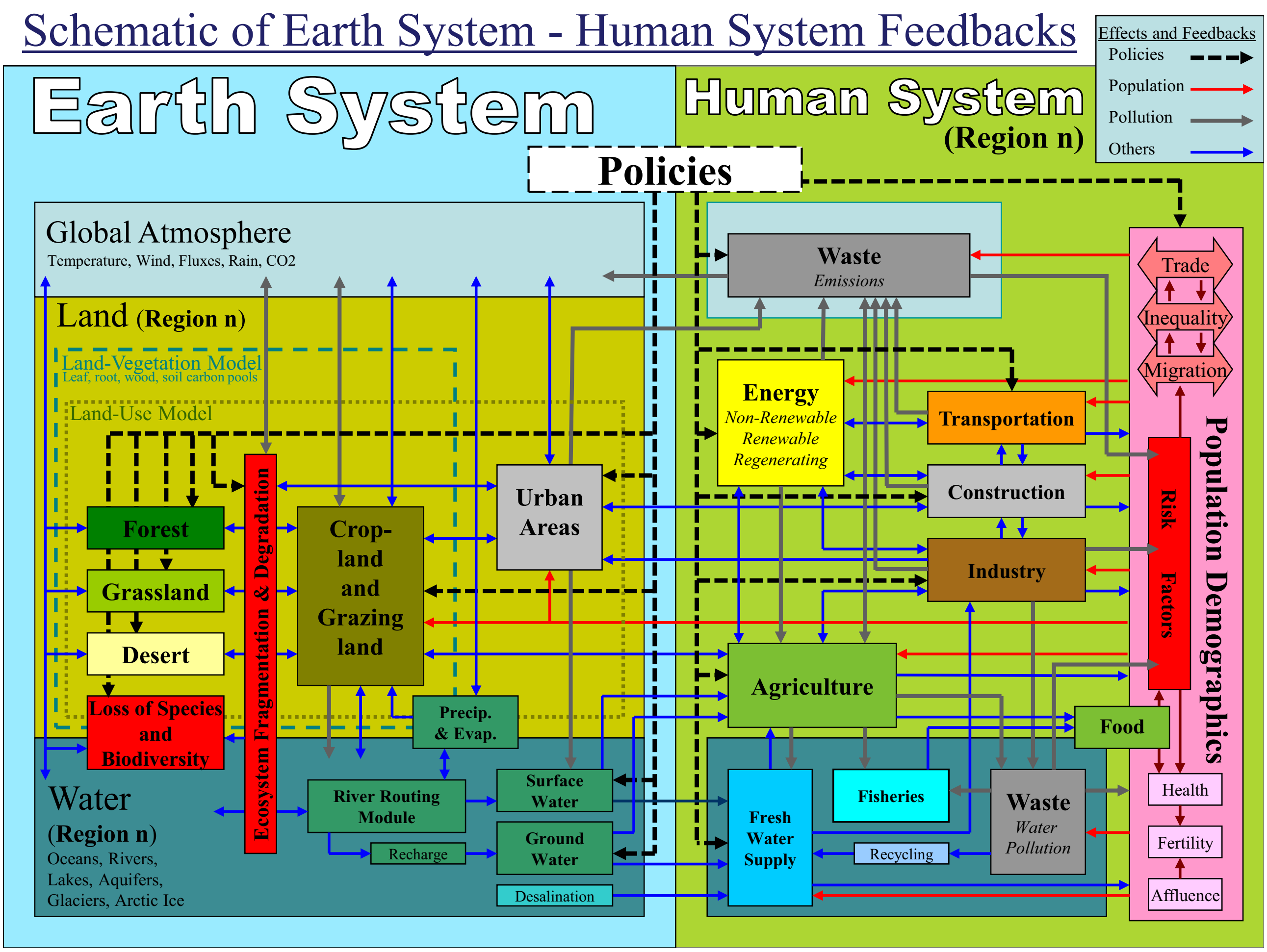

Figure 6. Schematic of a Human–Earth System with drivers and feedbacks.

needed feedbacks were described and interaction of the Earth System and the Human System was shown in the report, multiple subsystems of the Human System and feedbacks between those subsystems and with the Earth System were not fully included. The coupled framework proposed here includes the major subsystems and components of the Human System as well as their major feedbacks and risks, and explicitly recognizes policies as a major driver of the full system.

ESMs have long been based on integrating their dynamical equations numerically (e.g., numerical weather prediction models used by Weather Services). For Human Systems, Dynamic Modeling is also a powerful tool that scientists have successfully applied to many systems across a range of economic, social, and behavioral modeling [113,186–189]. The ability of dynamic models to capture various interactions of complex systems, their potential to adapt and evolve as the real system changes and/or the level of the modelers' understanding of the real system improves, their ability to model coupled processes of different temporal and spatial resolutions and scales, and their flexibility to incorporate and/or couple to models based on other approaches (such as agent-based modeling, stochastic modeling, etc.) render them as a versatile and efficient tool to model coupled Earth–Human Systems [190–193]. Since ESMs are already dynamic, a dynamic modeling platform would be a natural choice to model coupled Earth–Human Systems. Figure 7 is a schematic showing an example of a model to couple energy and water resources at the local and regional scales to human population.[28]

[28] Many of the variables in such a model are affected by processes at the global scale, while decisions are often made at a local scale. Choosing variables from the subsystems depends on the specific goals of the model. Reconciling various scales spatially or temporally can be done through downscaling, aggregating, and averaging for variables defined at smaller scales. Moreover, the Human System strongly influences consumption even at these smaller local scales. For example, Srebric et al. [297] show that not only population size but also behavior of people at the community scale strongly affects local energy consumption. This example shows that coupled Human System models are needed at various scales to project consumption patterns, especially for energy and water. We thank the anonymous Reviewer No. 2 for emphasizing the importance of coupling across various scales, and for many other helpful comments.

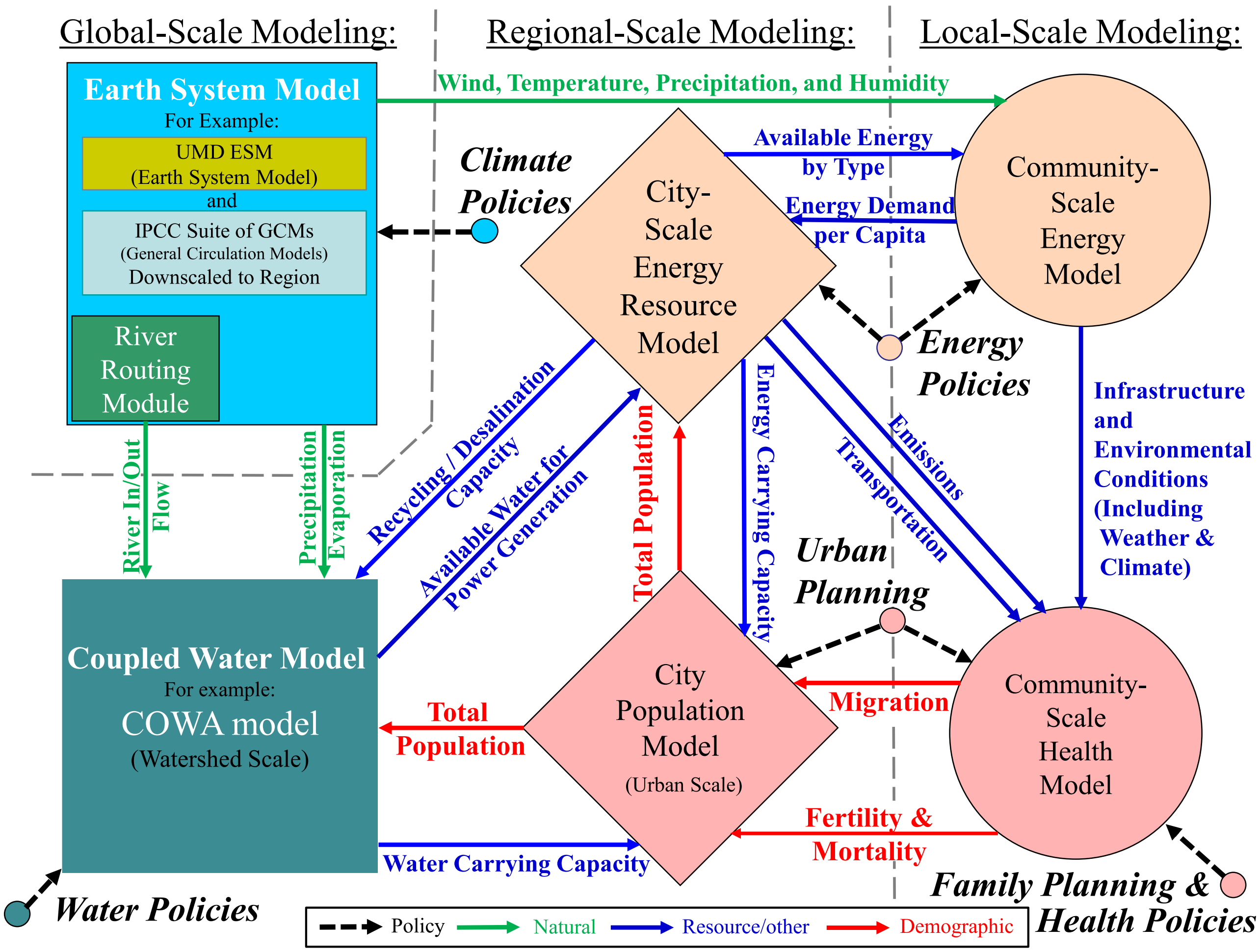

Figure 7. An example of a model schematic integrating water and energy resources with human population and health at the local and regional scales, coupled to an ESM at the global scale.

A major challenge in implementing such a framework of a coupled Earth–Human System is that it requires tuning many parameters to approximately reproduce its past observed evolution. This task has become easier over the last decade with the development of advanced methods of Data Assimilation commonly used in atmospheric sciences to optimally combine a short forecast with the latest meteorological observations in order to create accurate initial conditions for weather forecasts generated several times a day by the National Weather Services (e.g., [194–198]). The most methods (known as 4D-Var and Ensemble Kalman Filter) are able to go over many years of observations using a dynamic forecasting model and estimate the optimal value of model parameters for which there are no observations (e.g., [199–206]).

Uncertainty is another important challenge in producing future behavior and scenarios with models. This problem has been addressed successfully in meteorology by using, instead of a single forecast, an ensemble of typically 20–200 model forecasts created by adding perturbations in their initial conditions and in the parameters used in the models. These perturbations are selected to be compatible with estimated uncertainties of the parameters and initial conditions [207–210]. The introduction of ensemble forecasting in the early 1990s provided forecasters with an important measure of uncertainty of the model forecasts on a day-to-day and region-to-region basis. This made it possible to extend the length of the US National Weather Services weather forecasts made available to the public from 3 days to 7 days (e.g., [196]). A similar approach, i.e., running ensembles of model projections with perturbed parameters, could be used with coupled Earth–Human System models to provide policymakers with an indicator of uncertainty in regional or global projections of sustainability associated with different policies and measures. Calibration and tuning of coupled Human–Earth System models, as indicated above, could take advantage of optimal parameter estimation using advanced Data Assimilation, rather than following the more traditional approach of tuning individual parameters or estimating them from available observations.

Our proposed framework, together with Data Assimilation techniques, allows developing, testing, and optimizing measures and policies that can be implemented in practice for early detection of critical or extreme conditions that will lead to major risks to society and failure of supporting systems and infrastructure, and aid in the estimation of irreversible thresholds or regime-shifting tipping points [211–213]. Moreover, it allows for detecting parameters and externalities (such as inadequate measures or policies) that may play a significant role in the occurrence of catastrophes and collapses [214–217]. By adjusting the values of those parameters found to be influential through numerical experiments and simulations, short-term and long-term policy recommendations that can keep the system within optimum levels or sustainable development targets (e.g., Millennium Development Goals or the Post-2015 Development Agenda) can be designed and tested. This approach would allow policies and measures that have been found to be successful in specific cases to be modeled under different conditions or more generally.[29] Effective policies and measures are needed for all sectors of the Human–Earth System Model described above [184,218]. A dynamical model of such systems should be capable of testing the effects of various policy choices on the long-term sustainability of the system [215].

The track record until recently on climate change shows policy inaction is both dangerous and can be very costly [168,193,219]. And yet, despite a long history of scientific warnings (please see Footnote 30 for a detailed description[30]), the many current ecological and economic impacts and crises, the future risks and dangers, the large number of international meetings and conferences on the urgent need for climate policies and measures, and the adoption of some national and regional climate policies, growth in global CO_2 emissions from fossil fuels and cement has not only remained strong but is actually accelerating. The average annual rate of growth from 2000–2009 (∼2.9%) was almost triple the rate of the previous two decades, 1980–1999 (∼1.1%), while the most recent years, 2010–2012, have been even higher (∼3.4%) [127,220].

The sobering fact is that very little has been accomplished in establishing effective carbon reduction policies and measures based on science. The development and implementation of policies promoting sustainable technologies for the future (e.g., renewable energy sources) becomes even more challenging because of intervention and obstruction by a number of vested interests for continued and expanded use of their existing nonrenewable technologies and resources (e.g., some in the coal, oil, and gas industries). This is

[29] There are numerous examples of policies successfully tackling many of the challenges identified in this paper. For example, the province of Misiones, Argentina, with policies for forest protection and sustaining local incomes, stands out by having very high, remotely sensed values of NDVI (vegetation index) compared to the neighboring regions [298]. The state of Kerala, India, despite a very low GDP per capita (under $300 until 1990s), through policies expanding access to education and medical care, enjoys higher life expectancy, lower birth rates, lower inequality, and superior education compared to the rest of India [299–301]. Formal primary, secondary, and tertiary education can also reduce societal inequalities and improve economic productivity [98,182,184,302]. Education itself can also be offered in other forms. For example, education through mass media can be influential for changing long-term cultural trends and social norms, as can be seen in the successful attempt to reduce fertility rates in Brazil using soap operas [303]. There have also been other extremely successful noncoercive family planning policies, e.g., in Thailand, Mexico, and Iran [94,99,183,304–308]. A recent paper in PNAS [309] showed that slowing population growth could provide 16%–29% of the emissions reductions needed by 2050 and by 37%–41% by 2100, and a study by Wire [310] shows family planning is four times as efficient as adopting low-carbon technologies for reducing carbon in the atmosphere and ocean. Successful local and regional policies on air quality include California sharply reducing NO_2 in Los Angeles by 6.0 ± 0.7 % per year between 1996 and 2011 through strict policies on vehicular emissions [311]. Maryland succeeded in reducing SO_2 emissions per unit energy produced from power plants by ∼90% [312]. Regulations have reduced levels of SO_2 and NO_2 over the eastern US by over 40% and 80%, respectively, between 2005 and 2015. Over a similar period in India, these levels grew by more than 100% (SO_2) and 50% (NO_2), showing the possible dangers ahead absent effective policies [313].

[30] Anthropogenic climate change driven by carbon emissions, water vapor, and surface albedo was theorized as early as the 19th century, and an empirical warming trend was measured by the 1930s. Scientists came to understand the fundamental mechanisms of climate change by the 1950s and 60s (e.g., [314,315]). The first international scientific Conference on the Study of Man's Impact on Climate was held in 1971 and issued a report warning about the possibilities of melting polar ice, reduced albedo, and other unstable feedbacks that could lead to accelerated climate change 'as a result of man's activities' [316]. By 1979, a US National Academy of Sciences panel, chaired by Jule Charney, issued a report confirming the findings of climate change models [317], and over the course of the 1980s, the empirical evidence confirming ongoing climate change grew very rapidly. In 1988, James Hansen testified before the US Congress about the near certainty of climate change. The first IPCC Assessment Report was completed in 1990, and the Fifth in 2014, with each report successively warning of the increasingly grave consequences of our current trajectory. The latest report warns that without new and effective policies and measures, increases in global mean temperature of 3.7°C–4.8°C are projected by 2100 relative to pre-industrial levels (median values; the range is 2.5°C–7.8°C) [318]. Other national and global institutions have also warned of the disastrous consequences of such warming (e.g., [274]). As a recent World Bank assessment [261, p. xvii] states, 'The data show that dramatic climate changes, heat and weather extremes are already impacting people, damaging crops and coastlines and putting food, water, and energy security at risk...The task of promoting human development, of ending poverty, increasing global prosperity, and reducing global inequality will be very challenging in a 2°C [increase] world, but in a 4°C [increase] world there is serious doubt whether this can be achieved at all...the time to act is now'. Scientists have also long warned about the consequences of climate change for international security (e.g., [319–321]).

further complicated by some political rejection of science-based future climate projections and unwillingness to consider alternative economic development pathways to lowering the emission of carbon dioxide and other GHGs from the Human–Earth systems. However, the commitments to reduce carbon emissions by the vast majority of the world's countries in the recent agreement from the COP21 in Paris could signify a major policy turning point.[31]

One of the anonymous reviewers pointed out that the failure of policymakers to react sufficiently to the scientific understanding of global warming is paralleled by a similar failure with regard to scientific knowledge about population trajectories. Family planning policies have been pushed off policy agendas for the last few decades, and the subject of population has even become taboo. There are numerous non-evidence-based barriers that separate women from the information and means necessary to plan childbirths. The total fertility rate remains high in many countries not because women want many children but because they are denied these technologies and information, and often even the right to have fewer children. Access to family planning information and voluntary birth control is a basic human right and should be treated as such by international institutions and policy frameworks. Similarly, there is also an urgent need for improved educational goals worldwide. While these goals are repeatedly supported by both researchers and policymakers, policy implementation continues to be lacking. As a recent report by the Royal Society (the UK National Academy of Sciences) explains, improved education (especially for women) and meeting the large voluntary family planning needs that are still unmet in both developed and developing countries are fundamental requirements of future economic prosperity and environmental sustainability. This again emphasizes the critical need for science-based policies [98,182,184,218,221–227].[32]

[31] With more than 180 countries, covering ~90% of global emissions, having committed to submit INDCs, the Paris framework forms a system of country-level, nationally determined emissions reduction targets that can be regularly monitored and periodically escalated. While analysis [262] of the INDCs indicates that, if fully implemented, they can reduce the probability of reaching the highest levels of temperature change by 2100 and increase the probability of limiting global warming to 2°C, achievement of these goals still depends on the escalation of mitigation action beyond the Paris Agreement. Even if the commitments are fulfilled, they are not enough to stay below the 2°C pathway [261,262,322], but the Paris framework is an important start for an eventual transformation in policies and measures. Thus, the INDCs can only be a first step in a deeper process, and the newly created framework must form an effective foundation for further actions on emissions reductions.

[32] We thank anonymous Reviewer No. 1 for guiding us to add all the important points in this paragraph and the associated citations.

The importance and imminence of sustainability problems at local and global scales, the dominant role that the Human System plays in the Earth System, and the key functions and services the Earth System provides for the Human System (as well as for other species), all call for strong collaboration of earth scientists, social scientists, and engineers in multidisciplinary research, modeling, technology development, and policymaking. To be successful, such approaches require active involvement across all disciplines that aim to synthesize knowledge, models, methods, and data. To take effective action against existing and potential socio-environmental challenges, global society needs scientifically-based development of appropriate *policies*, *education* that raises collective awareness and leads to actions, investment to build new or improved *technologies*, and changes in *economic* and *social structures*. Guided by such knowledge, with enough resources and efforts, and only if done in time, human ingenuity can harness advances in science, technology, engineering, and policy to develop effective solutions for addressing the challenges of environment and climate, population, and development. Only through well-informed decisions and actions can we leave a planet for future generations in which they can prosper.

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