Impacts on Resources and Climate of Projected Economic and Population Growth Patterns *

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To this end, the Program brings together an interdisciplinary group from two established MIT research centers: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the Program's work lies MIT's Integrated Global System Model. Through this integrated model, the Program seeks to: discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is one of a series intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

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Global development and population growth are projected to seriously stress natural resources and alter the climate as soon as 2050.

Impacts on Resources and Climate of Projected Economic and Population Growth Patterns

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Global economic and population growth are driving energy, land, and water use, and there are complex connections between the use of these resources and the world's climate and natural environment.[1] A significant engineering challenge is to develop and deploy technologies that reduce human impact on the environment and make better use of resources while remaining robust in the face of unavoidable environmental change. Without significant changes in resource use patterns, projections indicate that fossil fuel use will continue to rise, more land will be converted for crops, and water stress will increase in many areas already subject to water shortages.

Even in the absence of climate and environmental change, these trends would lead to stress on water resources and natural systems as well as temperature increases of 3°C to as much as 8°C depending on the region and climate sensitivity. Higher global temperatures would be associated with an overall

[1] This paper draws on data and simulations from the MIT 2014 Energy and Climate Outlook. Complete data tables and figures are available at http://globalchange.mit.edu/research/publications/other/special/2014Outlook. In addition to the author, contributors to the Outlook are Sergey Paltsev, Erwan Monier, Henry Chen, Charles Fant, Jennifer Morris, Andrei Sokolov, Jin Huang, Kenneth Strzepek, Qudsia Ejaz, David Kicklighter, Stephanie Dutkiewicz, Jeffrey Scott, Adam Schlosser, Henry Jacoby, Audrey Resutek, Jamie Bartholomay, and Anne Slinne, all with the MIT Joint Program on the Science and Policy of Global Change.

increase in global precipitation (because a warmer climate speeds up the hydrological cycle, meaning more evaporation and more precipitation), but water runoff in many already water-stressed areas could be reduced, contributing to further water stress, with consequences for energy and food production.

This short paper presents a review of several key aspects of current global development to quantitatively describe how economic development drives energy, land, and water use and how the use of these resources may affect climate and the availability of resources.

Introduction: The MIT Integrated Global System Model (IGSM)

The elementary linkage of energy, climate, and the environment is a function of human use (combustion) of fossil fuels, emitting carbon dioxide (CO_2), a radiatively active gas, and leading to warming of the planet. The warming is augmented by positive feedbacks such as reduced ice and snow cover and increased water vapor. The warming and general changes in the climate then have impacts on the environment.

That characterization of the problem seems fairly simple. Deeper knowledge of the issues—and potential solutions—requires a better understanding of the underlying drivers and complex connections (Reilly 2013). To that end my colleagues and I apply the Massachusetts Institute of Technology (MIT) Integrated Global System Model (IGSM), a computer simulation model that represents explicit processes of earth systems (ocean, atmosphere, land surface, and freshwater) as well as an economic component that represents resource use and depletion, technical change, economic and population growth, and demand, supply, and trade in goods and services (Prinn 2012; Reilly et al. 2013).

The intent is not to predict what will occur but to give an idea of what is likely based on current givens. To the extent that the outcomes are undesirable, the scenarios presented can indicate what must be done—the engineering and technical challenges—to redirect growth and resource use for more sustainable or green growth.

Our projections incorporate key elements of existing policies and measures to which countries have committed in (as yet insufficient) attempts to stabilize the planet's climate, including the emissions targets in the Copenhagen-Cancún pledges agreed under the United Nations Framework Convention on Climate Change (UNFCCC) (UN 2009, 2010). These pledges focused on targets for 2020, which we extend through 2100, the horizon of our study. We include reductions beyond 2020 for the European Union (EU) to reflect targets proposed in its Emissions Trading Scheme (EU 2013), representing these targets by reducing the cap on emissions from power stations and other fixed installations by 1.74 percent every year.

Economic and Population Growth

Economic and population growth are key drivers of resource use, which can be moderated by both technical progress that enables more efficient use of resources and price changes that drive further conservation and efficiency measures.

Methodology

For expository purposes, we define three broad categories of countries based on their economic and population growth: *Developed*; an approximation of *Other* G-20 nations; and the *Rest of the World (ROW)*.

Developed countries and regions are Australia, Canada, the European Union plus Switzerland, Norway, and Iceland, Japan, New Zealand, and the United States. The *Other G-20* countries comprise several large economies that have made rapid progress toward development in recent years, including China, India, Brazil, Mexico, Russia, and several rapidly growing Asian countries. We use the G-20 designation to recognize the growing importance of these additional countries to the global economy, but because our regional modeling does not allow us to aggregate to the exact G-20 group we also include Malaysia, the Philippines, Singapore, Taiwan, and Thailand, which are part of our "Dynamic Asia" region.[2] G-20 members Argentina, Saudi Arabia, South Africa, and Turkey are included in our *ROW* group because we don't separate them from broader regional groups, shown in figure 1.[3]

Findings

Underlying the economic scenario are population projections drawn from the UN's 2012 Revision (UN

[2] The actual members of the G-20 are Argentina, Australia, Brazil, Canada, China, the European Union, France, Germany, India, Indonesia, Italy, Japan, the Republic of Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, the United Kingdom, and the United States.

[3] The underlying projections at this level of disaggregation are from the 2014 Energy and Climate Outlook (see footnote 1).

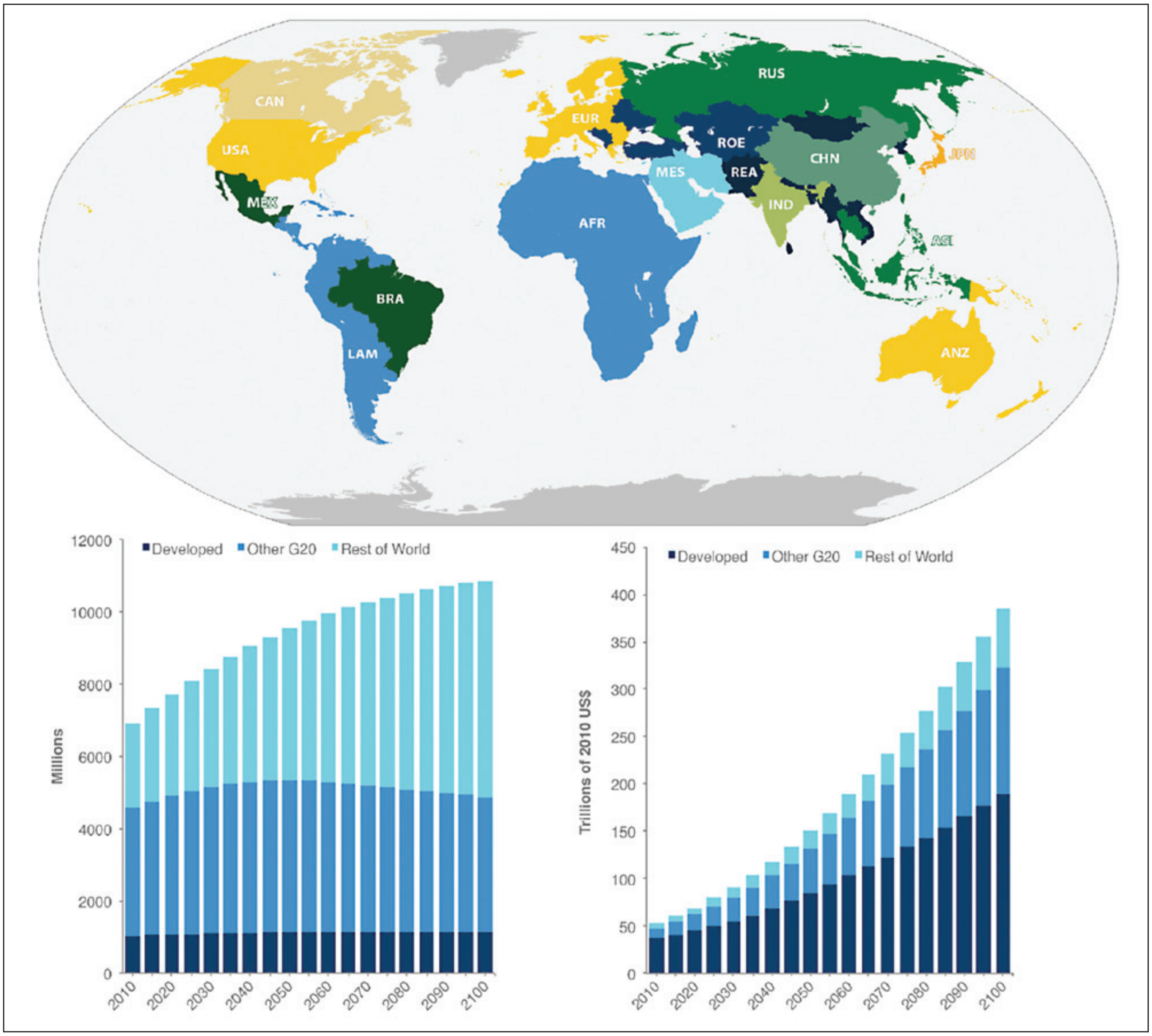

FIGURE 1 Regions of the MIT Integrated Global System Model (IGSM), population, and gross domestic product (GDP). The regions shown in the map are aggregated into 3 broad country groups: *Developed* countries (in yellows); an approximation of *Other G-20* nations (greens); and the *Rest of the World* (blues), for all of which we report forecasts for population (bottom left) and GDP (bottom right). By 2050, the *Developed* region accounts for 56% of GDP, evaluated at market exchange rates in the base year of the model, and only 12% of the population. ANZ = Australia & New Zealand; ASI = Asia; LAM = Latin America (not including Brazil); MES = Middle East; REA = other East Asia; ROE = rest of Europe. Sources: Population estimates are from UN (2013); GDP and all other projections and data are from the MIT 2014 Energy and Climate Outlook (see footnote 1).

2013), projecting a global population of about 9.5 billion by midcentury and 10.8 billion by 2100. Gross domestic product (GDP) growth is projected based on assessments of growth in the productivity of labor, land, energy, and endogenous savings and investment. These factors are more than enough to offset effects of resource depletion and other limits on natural resource availabilities.

Population assumptions show stable or declining levels in *Developed* regions, stabilization in the *Other G-20*, and continued increases in the *ROW*. By 2050 about 88 percent of the world's population will be in the *Other G-20* and *ROW*.

Productivity changes in the near term are adjusted to generate GDP growth projections, which are consistent with those of the International Monetary Fund

(IMF 2013) and similar to other long-term projections in that the *ROW* and *Other G-20* regions grow at a faster rate than the *Developed* countries. Even so, the disparity remains in terms of the fraction of economic activity, and declines only slowly.

In 2050 the *Developed* region will account for 56 percent of GDP (evaluated at market exchange rates in the base year of the model) and 12 percent of the population. However, that fraction of GDP is down from 71 percent in 2010. Evaluating GDP using a purchasing power parity (PPP) index would substantially upweight both current and future levels of economic activity in the *Other G-20* and the *ROW*, as well as their shares, compared with our use of market exchange rates (World Bank 2015). Absolute shares are subject to these caveats, but the more rapid growth we show for the *Other G-20*, as evident in figure 1, would be preserved if converted to PPP.

China is the largest economy in the *Other G-20*: it has been growing at around 10 percent per year or more over the past decade. Our forecast, consistent with internal projections in China, shows its growth slowing gradually to 3.0 percent by 2050. Even then, the *Other G-20* will outperform the other regions by a substantial margin.

Accounting for Regional Differences in Energy Consumption

An economy's energy consumption is a combination of household use, energy needed for infrastructure development, and energy used in the production sector. Our modeling framework has a full representation of depletable resources such as oil, coal, and gas; renewable resources such as land (which can be used to produce bioenergy in addition to conventional agricultural crops), wind, and solar; the technologies available to use these resources; and industrial and residential sectors that create demand for energy (Reilly et al. 2011). We further explicitly represent trade, because some low-energy or -emissions countries or regions may appear low in part because of large energy or emissions embodied in their trade.

Implicit in the representation of demand is a changing structure as economies become wealthier. In general, we see an energy-to-GDP elasticity of less than 1—that is, a 1 percent increase in GDP leads to a less than 1 percent increase in energy—in all regions, but it is much lower in heavily developed countries.

Many *ROW* members are still in the process of infrastructure development or cannot meet basic energy needs, hence more rapid growth in commercial energy demand relative to GDP. The *Other G-20* countries have more infrastructure development and are at a stage where income levels permit households to afford energy-intensive goods like private automobiles. Our projections show their economies growing rapidly.

These factors, in combination with differential emissions policies (e.g., more stringent in the *Developed* region), lead to the energy use projections shown in figure 2: flat or declining in the *Developed* region, rapidly growing in the *Other G-20*, and rising in the *ROW*. In fact, the *Other G-20* becomes an energy world of its own by 2050, with energy use as big as total global energy use today.

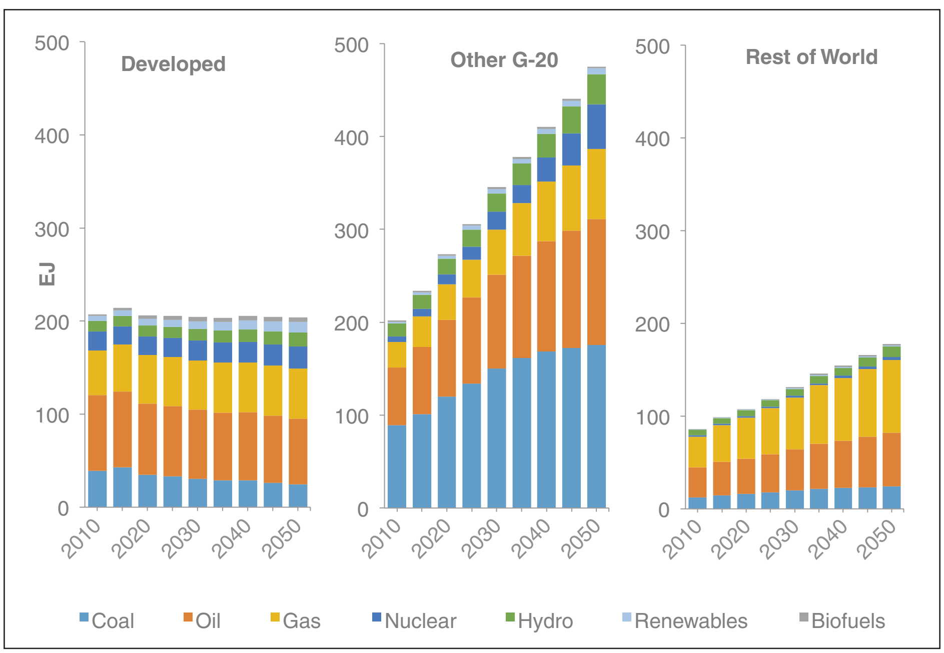

FIGURE 2 Primary energy use by major group, in exajoules (EJ), 2010–2050. We project flat or declining energy use in the *Developed* region, rapidly growing energy use in the *Other G-20*, and continued growth in the *Rest of the World*. By 2050, energy use by the *Other G-20* is as big as total global energy use today. See text for definitions of country groupings.

Emissions and Climate Implications

Total greenhouse gas (GHG) emissions from all sources of human activity—energy, industry, agriculture, waste, and land use change—are projected to reach 76 gigatonnes (Gt) CO_2-equivalent by 2050, and 92 Gt by 2100 if basic economic and policy drivers remain unchanged, nearly doubling from an estimated 49 Gt in 2010.

Sources of Emissions

Fossil fuel CO_2 emissions account for about two thirds of GHG emissions, basically unchanged throughout the forecast period, and about one third is from other sources. In 2050, CO_2 from fossil energy combustion will be about 49.9 Gt, CO_2 from cement and land use change roughly 7.6 Gt, methane about 12.5 Gt CO_2-equivalent, and nitrous oxide about 5.4 Gt CO_2-equivalent (other gases together will account for less than 1 Gt CO_2-equivalent).

Regional emissions reflect, to a large degree, regional energy use. The *Other G-20* countries are projected to contribute 43 Gt of emissions in 2050, of which 21 Gt will be from China and 11 Gt from India. The *Developed* region, because of policies in the Copenhagen-Cancún agreements, will emit just under 12 Gt, down from 14 Gt in 2015, while emissions from the *ROW* will have grown from about 13 Gt in 2015 to 22 Gt.

Emissions of long-lived GHGs combined with changing emissions of short-lived species (e.g., black carbon, sulfate aerosols, and their precursors; tropospheric ozone precursors) contribute to changes in concentrations of radiatively active species in the atmosphere. And they are in addition to the previous contributions to these concentrations, such as those of chlorofluorocarbons (CFCs), whose use has already been phased out but which remain in the atmosphere, and feedbacks from natural sources (or sinks) of carbon dioxide, methane, and nitrous oxide as they are affected by changes in climate or concentrations of the pollutants themselves.

Carbon dioxide concentrations are expected to reach about 530 parts per million (ppm) by 2050 and 750 ppm by 2100, with combined radiative forcing of all GHGs up to 5 watts/meter^2 (W/m^2) by 2050 and 7.3 W/m^2 by 2100. This is somewhat less than the highest scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) in its Reference Concentration Pathways (RCPs) (van Vuuren et al. 2011) and Special Report on Emissions Scenarios (SRES) (Nakicenovic

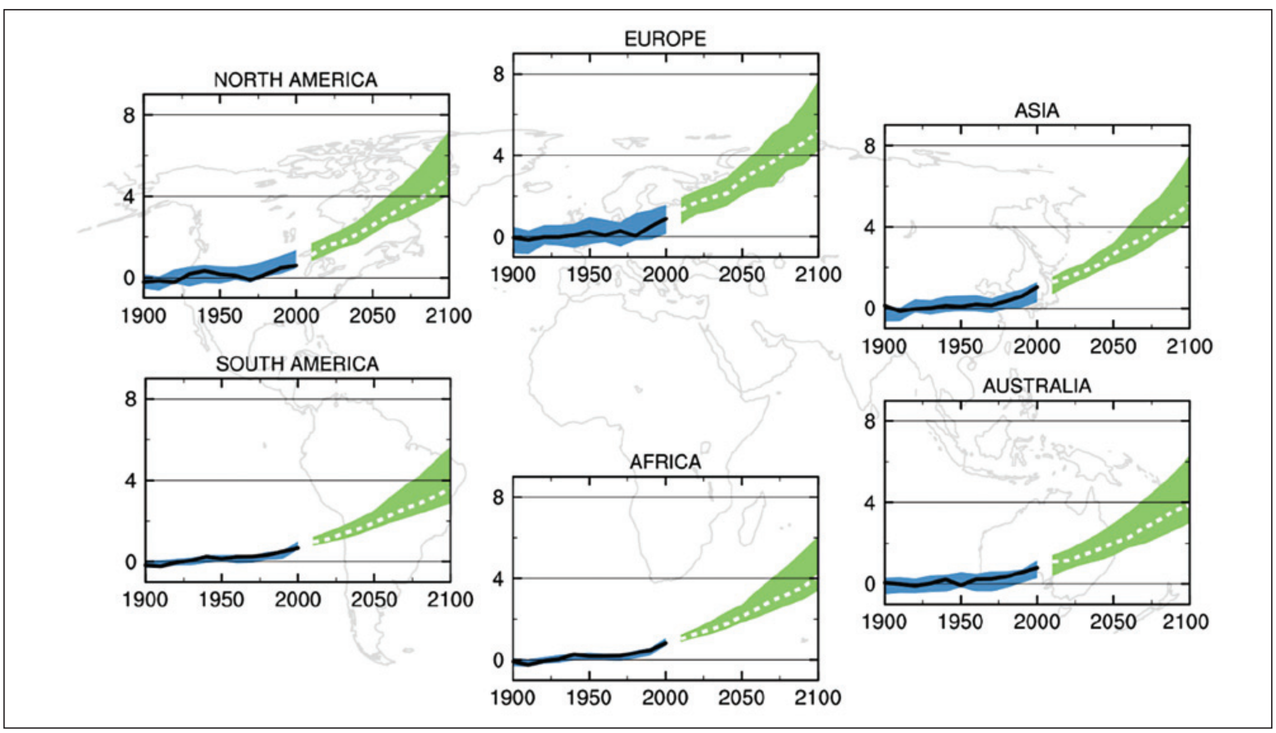

FIGURE 3 Regional temperature change, 1900–2100. Black lines represent observations; blue bands show the range of simulations over the historical period; white dotted lines show the mean of model runs, with five different initial conditions for the median climate sensitivity; green bands represent the range over all climate sensitivity scenarios and initial conditions for projections over the 21st century. All continents are projected to experience large increases in temperature.

and Swart 2000), which project 8–8.5 W/m^2 by 2100. But our projections remain above RCPs with policies that aim at stabilizing radiative forcing below 6.0, 4.5, and 2.6 W/m^2 through 2100.

The projections clearly show that the current path of development and policy efforts are both insufficient to achieve even a comparatively modest stabilization goal of 6 W/m^2 over the longer run.

Consequences

The environmental and climatic consequences of the projected levels of GHG and other pollutant emissions include changes in ocean acidification, temperature, precipitation, sea level rise, and vegetation. We take into account current knowledge of the global climate system response by sampling climate sensitivity (defined as the change in global mean temperature in response to a doubling of atmospheric CO_2 concentrations), using the 5th percentile (2.0°C), median (2.5°C), and 95th percentile (4.5°C) of its probability density function (see Monier et al. 2013).

In addition, in light of the large role of natural variability in projections of temperature and precipitation at the regional level (Monier et al. 2014), we use five different initial conditions for each climate sensitivity scenario in order to account for the uncertainty in natural variability. We show the range of mean surface temperature changes since 1900, along with projections for 2100, for six continental regions (figure 3).

All continents are projected to experience large increases in temperature by 2100: greater than 3°C in South America, Africa, and Australia and over 4°C in North America, Europe, and Asia. The range of projected warming is large (from 3°C to almost 8°C), indicating that there is considerable uncertainty in the projections, and this uncertainty increases over time. Nonetheless, there is also a good deal of certainty that future changes in temperature for all continents will be unprecedented.

Land and Water Resources

Changes in demand for different types of land are driven by growing population and changing consumption patterns over the forecast period. These supply and demand changes can be offset by technologies that improve yields over time and are resolved in markets through price hikes for commodities and resources. Higher resource prices can spur more intensive agricultural production practices in an effort to close imbalances.

Land Resources

The total land area of each of our three regions will remain the same, but its allocation to different purposes will affect the balancing of supply and demand both within regions and globally (figure 4).

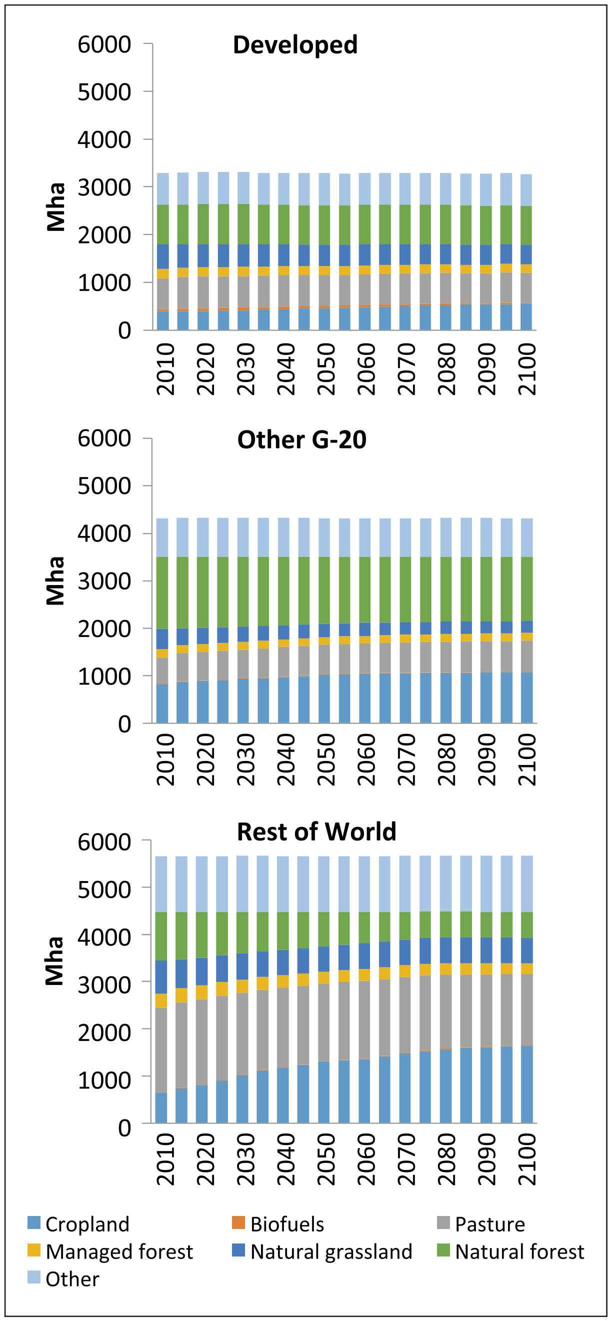

FIGURE 4 Land use by major group, millions of hectares (Mha), 2010–2100. All regions see some increase in cropland, but it is much greater in the *Rest of the World* as food demand rises faster in association with more rapid population growth and rising incomes. See text for definitions of country groupings.

Countries and regions exhibit not only a preference for commodities produced domestically but also differing willingness to convert unmanaged land to cropland, pasture, and managed forest; developed countries, for example, have forest and land protection policies in place and enforce them. This combination of forces gives rise to the regional patterns of land use change.

All regions see some increase in cropland, but it is much greater in the *ROW* as food demand is increasing faster due to more rapid population growth and rising incomes. With both the preference for domestically produced goods and greater willingness to convert unmanaged lands, there is more deforestation in these countries, as opposed to little if any in the *Developed* and *Other G-20* regions.

Food demand is increasing faster due to more rapid population growth and rising incomes in the developing world.

The pattern is quite different from that of energy use, where the biggest changes are in the *Other G-20*. This reflects the impact of the faster-growing population in the *ROW* on food demand, as opposed to the stronger effect of per capita income growth on energy demand in the *Other G-20*. Of course, deforestation is a source of CO_2 emissions when the biomass is burned or decomposes. This source of emissions is included in the MIT IGSM and in the projections discussed above.

Water Resources

Fresh water is a critical resource for the planet. The specific pattern of precipitation changes is highly uncertain and varies among climate models, but overall, and consistent with all global climate models, it is quite certain that with warming global precipitation will increase. The impact on freshwater resources will depend on how precipitation changes over land.

In our modeling we project the global annual amount of freshwater flow to increase by about 15 percent by 2100—and total water withdrawals for human uses to increase by about 19 percent. Water needed to maintain water-related ecosystems will increase by a similar amount. Much of the change in withdrawals will result from increasing economic activity and population growth, largely in tropical and subtropical developing countries, which are located primarily among the *Other G-20* countries and the *ROW*. Increases in water use rates tend to slow as per capita income rises (the income elasticity of water demand falls with income) and is near zero in highly developed countries.

To summarize the impacts of climate change and economic growth on water resources, we use a *water stress index* (WSI), defined as a ratio of total water requirements (municipal, industrial, energy, and irrigation) to freshwater flow (water from upstream sources and basin runoff). We further characterize our calculation as *potential water stress*, as our framework does not consider adaptation to changes in flow, which would inevitably occur. The index can take values from 0 (no water withdrawal requirements in the basin) to greater than 1.0 (the combination of growth and changing resources leads to water requirements greater than average annual flow). The water resource literature considers a WSI larger than 0.6 as indicative of severe water stress (Schlosser et al. 2014; Strzepek et al. 2013).

It may appear overly conservative that serious water stress conditions exist when as much as 40 percent of the annual freshwater flow in a basin is unused, but at least three factors must be considered: (1) most water basins have wet and dry seasons, and if 60 percent or more of the annual flow is being used shortages are likely during the dry season; (2) there is increasing concern about the downstream environment of water systems, with regulations or guidance on maintaining a minimum flow level to preserve freshwater systems that depend on river flows; and (3) most regions are subject to large interannual and even decadal variability in river flows, so using a large proportion of the average annual flow can create vulnerability during year-long or multiyear droughts (Smakhtin et al. 2005).

We map current stress and the change in water stress from 2010 to 2100 as estimated from our climate and economic projections (figure 5). Although our scenarios show reductions in water stress in some parts of North America, China, and the Middle East by 2100, the risk of water stress will increase in parts of India, China, Pakistan, Turkey, North and South Africa, and the United States, in many areas that are already stressed or severely stressed.

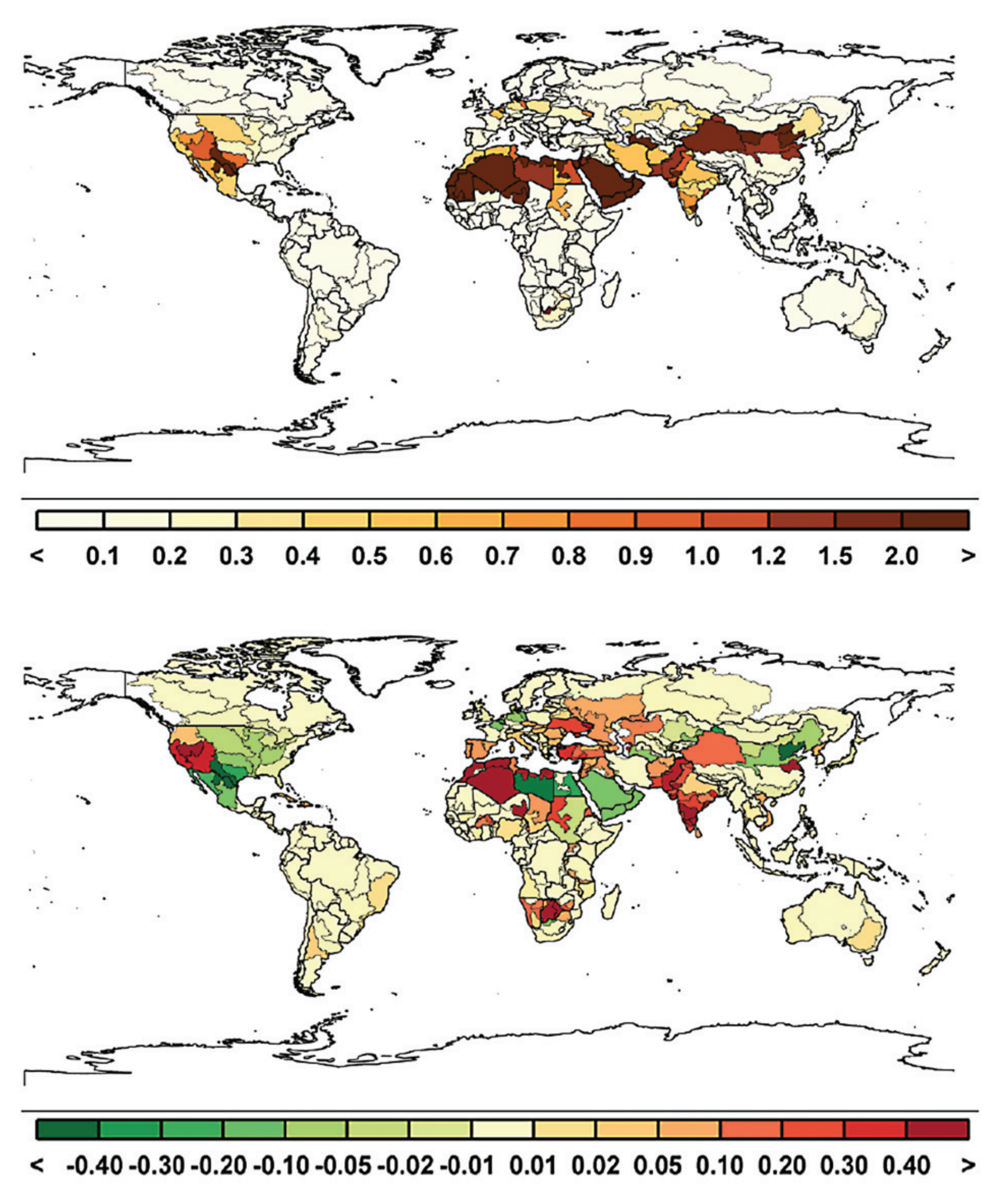

FIGURE 5 Water stress indices, 2010 and 2100. The top map index is the ratio of water demand to available annual flow. A ratio above 1.0 indicates either unsustainable demand met by depletable groundwater or unmet demands. The index in the bottom map is the difference between the top index calculated for 2100 minus the index for 2010. For the bottom map, oranges and reds show areas of increasing stress, greens show areas of decreasing stress. Many of the areas that show increased stress are already moderately or heavily exploited. Smakhtin et al. (2005) used the following designations: 0.3 ≤ WSI < 0.6 = moderately exploited, 0.6 ≤ WSI < 1 = heavily exploited, 1 ≤ WSI < 2 = overexploited (WSI = water stress index).

Engineering and Technical Challenges

Absent much stronger measures to reduce greenhouse gas emissions the world will see rising temperatures and changes in land use and water resources. The engineering and technical challenges involve inventing and improving on alternative energy technologies that produce low or no GHG emissions and scaling these technologies to meet global energy needs.

> *Engineering challenges involve inventing energy technologies to produce low or no GHG emissions and scaling them for global energy needs.*

In 2010 renewable energy, including commercial biomass, wind, and solar, contributed only about 2 percent of global energy needs; nuclear and hydro contributed about 12 percent. Our projections show global energy use increasing more than 70 percent by 2050. There may be technical solutions to improve energy efficiency and perhaps slow demand growth, but persistent unmet energy needs outside of the developed regions of the world will at least partly offset efficiency gains.

To eliminate CO_2 emissions associated with fossil fuels, further electrification of the global economy is likely needed, but there is a long way to go to achieve this. To produce as much electricity as coal, oil, and gas did in 2010, renewable electricity would need to increase 16-fold from its 2010 level, and nuclear would need to increase 4.5-fold. There is potential for more hydro development in some parts of the world, carbon capture from large point sources such as coal or gas power plants is an option, and biomass energy could supply a substantial portion of the world's energy needs under the right conditions.

But each of these alternative energy sources faces technical challenges. Intermittent renewable electricity such as wind and solar must be integrated into the electric grid and supplies balanced to meet demand through either dispatchable sources of supply or energy storage. Despite significant efforts to make nuclear energy safe, combinations of human error (Three Mile Island, Chernobyl) and designs that were not resilient to extreme events (Fukushima) have undermined public confidence in these technologies and significantly increased costs. Hydropower resources are more limited and in some regions have been largely tapped out; but the bigger limit on development of this resource may be the ecological and social implications of large dams that flood unique natural ecosystems and extensive human settlements.

The development of cost-effective carbon capture and storage (CCS) has been elusive, with significant cost overruns at large-scale demonstration plants leading to cancellation of more extensive plans to develop the technology. If CCS were scaled up to capture a significant share of CO_2 emissions, a major transport system, likely involving pipeline, would need to be developed to get the CO_2 from points where it is produced to locations where it could be stored underground. With biomass energy, the dual concerns are excessive land use (and deforestation) and pressure on food prices if it uses a significant amount of the world's available cropland. If these challenges are not met there will be substantial warming and problematic changes in resources, as described in our simulations.

In addition to the concerns about land allocation and use, increases in water stress will require some combination of additional storage capacity in reservoirs, interbasin transfers of water, development of other sources of fresh water such as desalinization or recycling of grey water, greater efficiency in use, and ultimately the possible relocation or redirection of the growth of water-using activities toward river basins with adequate resources. Water scarcity is not the only potential problem. Changes in water temperatures would limit the use of water for thermoelectric cooling. And in areas where water scarcity is not a concern, the opposite problem of flooding may require engineering solutions to protect infrastructure.

It is widely recognized that mitigation (limiting GHGs) requires global cooperation and public policies that thwart private sector incentives to continue to burn cheap fossil fuels without capturing the carbon emissions. Greater public funding for research and development is likely needed, although directly pricing carbon could motivate private firms to undertake much of the development, demonstration, and scaling up of new low-carbon technologies.

Private firms and local and regional governments are already beginning to factor changing climate into their decisions. Failure to do so will affect their bottom lines and the cost of maintaining critical infrastructure.

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