Land's complex role in climate change

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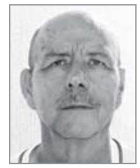

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To mitigate climate change at local, regional, and global scales, we must begin to think beyond greenhouse gases.

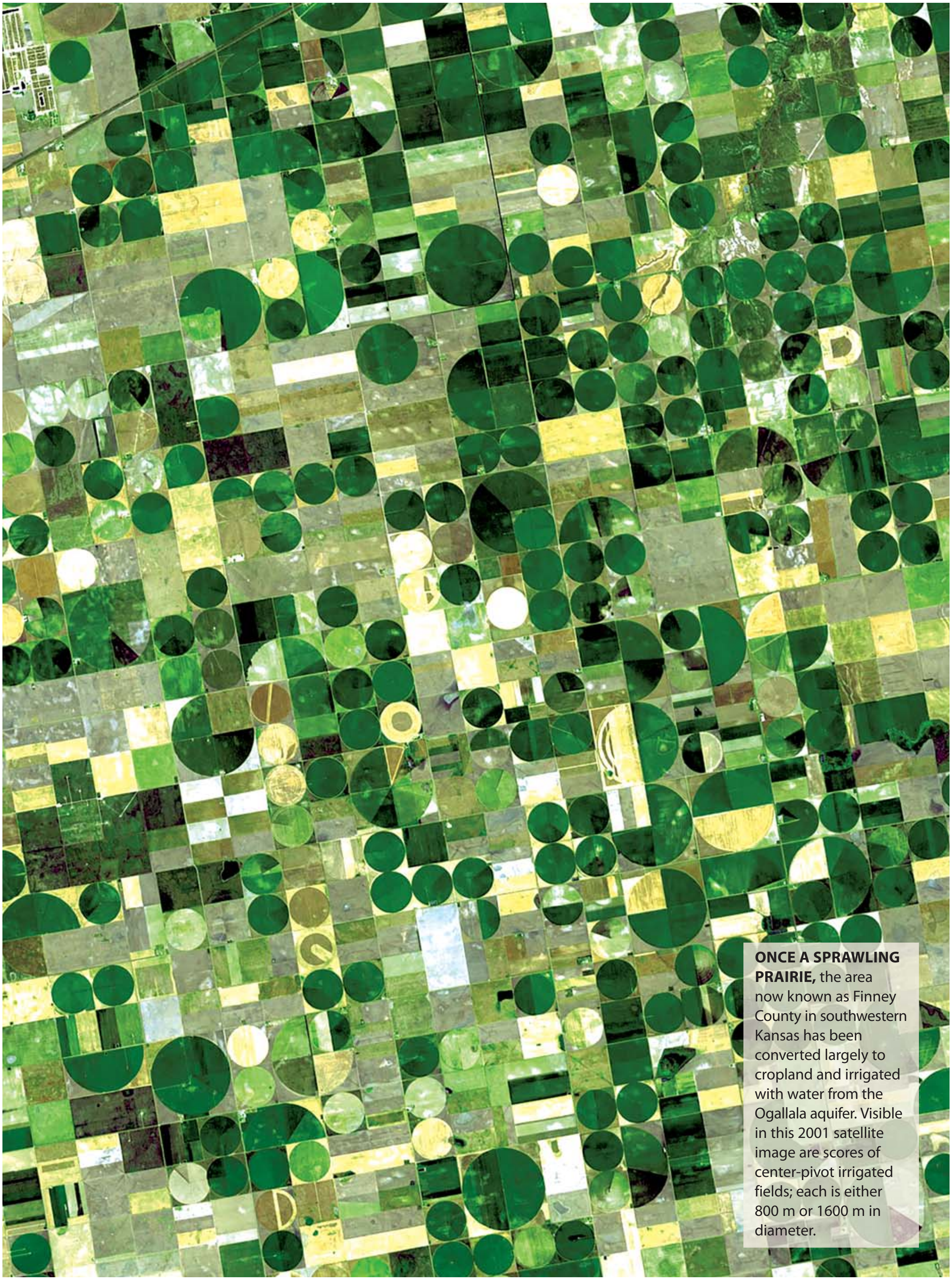
To date, most reporting on climate has focused on the possibility of catastrophic warming due to carbon dioxide and other greenhouse gases released into the atmosphere. The assessment of climate change risk has essentially been distilled to a single metric: the global average surface temperature. That reality was evident at the 2015 United Nations Climate Change Conference in Paris, where the central negotiating point was whether the global temperature rise should be limited to 1.5 °C or 2 °C. Indeed, a 2016 opinion piece by Simon Lewis (University College London and the University of Leeds, UK) states that, "by endorsing a limit of 1.5 °C, the [Paris] climate negotiations have effectively defined what society considers dangerous."[1]

But the reality of humans' impact on climate is exceedingly complex.[2] Even if greenhouse gas emissions could be eliminated completely, other harmful anthropogenic sources of climate change would remain. And even if global average temperatures were contained, human impacts on climate would manifest in other potentially dangerous ways.

One often overlooked human factor is land use. Deforestation, dryland farming, irrigated agriculture, overgrazing, and other alterations to the natural landscape can disrupt Earth's natural balances and change weather patterns. As with the addition of CO_2 into the atmosphere, the effects can last for decades or longer and affect regions distant from the original offense. Given continued rapid population growth, they threaten to be irreversible.

By focusing only on greenhouse gases and warming, we diminish our ability to respond to the diversity of human influences on climate and to the effects of natural variability and long-term change. In a 2005 article on NASA's Earth Observatory website, Gordon Bonan of the National Center for Atmospheric Research framed the issue in no uncertain terms: "Nobody experiences the effect of a half a degree increase in global mean temperature. . . . Land cover change is as big an influence on regional and local climate and weather as doubled atmospheric carbon dioxide—perhaps even bigger."[3]

In this article we argue that the impacts of modification and management of the land and other human effects on climate merit the same level of research and policy attention given to greenhouse gas effects. The inherent complexity of accounting



NASA

ONCE A SPRAWLING PRAIRIE, the area now known as Finney County in southwestern Kansas has been converted largely to cropland and irrigated with water from the Ogallala aquifer. Visible in this 2001 satellite image are scores of center-pivot irrigated fields; each is either 800 m or 1600 m in diameter.

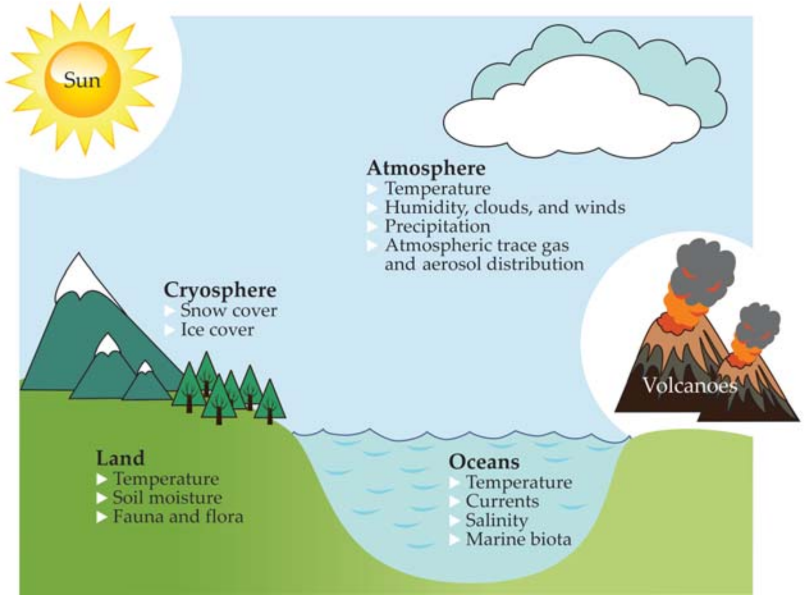


FIGURE 1. THE CLIMATE SYSTEM consists of the atmosphere, cryosphere, land, and oceans, each of which can be characterized by a set of state variables. Climate change is said to occur when a forcing generates an intercomponent flux of energy, mass, or momentum that inflicts prolonged changes to one or more state variables. The forcing may originate from within the climate system itself or from a source such as solar, volcanic, or human activity. (Adapted from ref. 4.)

for all those factors will require redefining the way we think about the risks of climate change.

Not just warming

To fully appreciate the scope and diversity of climate change, one first needs a clear understanding of what is meant by climate. As illustrated in figure 1, the climate system consists of the atmosphere, oceans, land, and the ice- and snow-covered regions known collectively as the cryosphere. Each system component can be characterized by certain state variables—atmospheric temperature, ocean salinity, land moisture, and depth of snow cover, to name a few.

Climate change occurs when a perturbation—a forcing, as it's known in Earth-science parlance—generates a flux that alters the components' natural states. A 2005 US National Research Council report more precisely defines climate change as any multidecadal or longer alteration in one or more physical, chemical, or biological state variables or fluxes within the climate system.[4] The time scale of several decades is typically used to distinguish climate change from short-term variations in weather and other aspects of climate.

Of course, Earth's climate is always changing, so in a sense, the "change" in climate change is redundant. In addition to anthropogenic contributions, climate is subject to both internal forcings—from ocean currents, atmospheric currents, and the like—and external forcings such as solar variability and volcanic activity. The term "change," however, is generally used by policymakers to imply change resulting from human actions.

Global warming, the increase in the average heat content of the climate system, is one type of change. It is best characterized in terms of the spatially integrated temperature of the ocean—where more than 90% of heat change occurs—and is expressed in units of joules. A two-dimensional global average of surface temperature trends is therefore an imperfect metric to diagnose global warming. It's also inadequate to characterize the many facets of climate change.

Arguably, the aspects of climate that most affect us and our environment at local and regional scales are those that influence weather patterns—droughts, floods, tropical cyclones, heat waves, and so forth. (Sea-level rise is one regionally important aspect of climate that is not directly linked with weather.) Weather patterns are influenced primarily by regional atmospheric and ocean circulations such as El Niño, the North Atlantic Oscillation, and the Pacific Decadal Oscillation. Changes in those circulations should be of even greater concern than globally averaged properties. (See the article by Thomas Birner, Sean Davis, and Dian Seidel, PHYSICS TODAY, December 2014, page 38.)

Regional weather patterns are, in part, a function of land cover. Modifications to the biophysical characteristics of the land and to the way we manage it can alter the relative abundances of carbon, nitrogen, and other trace gases and aerosols near Earth's surface and the fluxes of water, heat, light, and momentum between components of the climate system.[5,6] To see how land-cover change can directly impact climate, let's consider an example: irrigation.

The turf and the tempest

The irrigation of semiarid land can dramatically alter a region's water balance.[7] Due to the combined effects of evaporation and transpiration, collectively termed evapotranspiration, increases in ground moisture tend to raise humidity in the overlying atmosphere. Such increases in humidity can mean the difference between a mild shower and a torrential downpour.

To understand how, consider the concept of moist static energy, S, which can be expressed as

$$S = C_p T + Lq.$$

The term $C_p T$ represents sensible heat—the heat derived from an increase in temperature T. The term Lq represents latent heat, a potential energy that's stored in the vapor phase during the process of evaporation. Here, C_p is the specific heat of water at a constant pressure, L is water's latent heat of vaporization, and q is specific humidity—the mass ratio of water vapor to air.

In essence, S is a measure of the buoyant potential energy. Thunderstorms feed on that energy; the larger it is, the more intense a storm can become. The irrigation of a dry patch of land boosts S by increasing q.

The effect can be dramatic: At atmospheric pressure, a mere 1 °C rise in dew point from 23 °C to 24 °C—equivalent to an increase in q of 1 g/kg—would have the same effect on S as a 2.5 °C rise in temperature. (The same humidity increase would have a smaller effect in a cooler atmosphere and a larger effect in a warmer one.) The increase in moist static energy due to humidity would be partially offset by a reduction in T from the cooling effects of evapotranspiration, and the chances of triggering a thunderstorm by surface heating would also decrease.

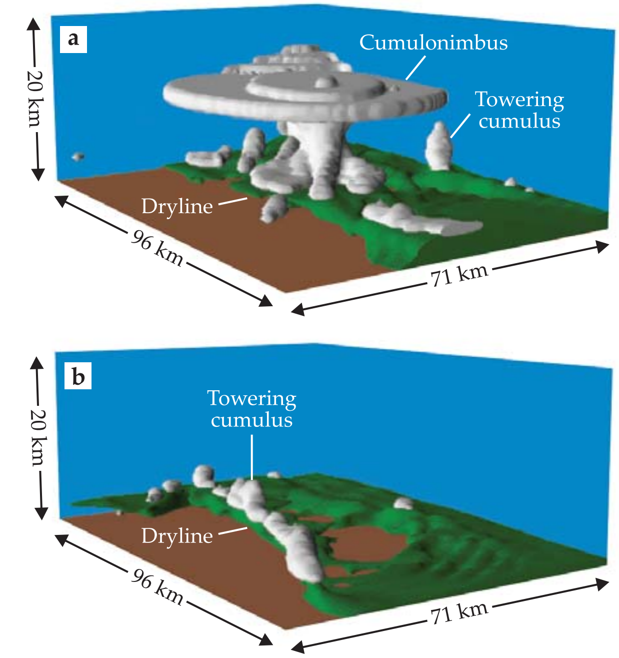


FIGURE 2. SIMULATIONS OF ATMOSPHERIC CONDITIONS over a 7000 km^2 swath of the US Great Plains on 15 May 1991 demonstrate the intimate link between the landscape and weather patterns. **(a)** A simulation of the terrain in its actual state—covered with a mix of shortgrass, farmland, and brush—predicts the formation of rain-generating cumulonimbus clouds. (That model prediction bore out in real life.) The dryline marks the boundary between the moist eastern air (green) and the dry desert air (brown) to the west. **(b)** In an alternate scenario where the land is covered entirely by dry shortgrass, towering cumulus clouds form but no storms develop. (Courtesy of Conrad Ziegler, NOAA.)

However, if a thunderstorm were to form, it would likely be more intense and produce more precipitation.

Figure 2 shows an illustrative case study: a weather simulation of 7000 km^2 of farmland, brush, and shortgrass in the Great Plains region of the US.[8] In a simulation using that terrain as it was on 15 May 1991, evapotranspiration generates enough atmospheric moisture and moist static energy to produce heavy rainfall and thunderstorms. But in a scenario in which the terrain is covered by only dry shortgrass—as it was before human influences—no storms form.

Unfamiliar terrain

Examples of large-scale, human-driven landscape transformations are increasingly easy to find. The human footprint on the land is vast and expanding, driven largely by the growth and intensification of agriculture.[9] (See figure 3.) Global cropland cover is estimated to have increased from 300 million hectares to 1530 million hectares between the years 1700 and 2000.

Even in some areas where the land cover has not changed, the manner in which the land is used has. Between 1700 and 2000, for example, the global area used for grazing livestock increased 10-fold, from 324 million hectares to 3429 million hectares. By 2000 only a few desert regions, the central Amazon and Congo basins, arid areas of Australia, and the Arctic and Antarctic had not been significantly affected by humans. Roughly half of Earth's land surface is estimated to have suffered intensification in land use.[10] Such shifts in land management can drastically alter carbon, heat, and water fluxes between the surface and the overlying atmosphere. (See the box on page 45.)

The growing human footprint on the landscape is disquieting in part because of the sheer magnitude of its effect. In parts of Arizona, urbanization-induced warming—commonly known as the urban heat-island effect—could boost temperatures by up to 7 °C in coming decades, nearly three times the predicted rise in temperature attributable to greenhouse gas emissions.[11] (See figure 4 for a visual illustration of the heat-island effect in London.)

Changes in land cover and management have large impacts at local and regional scales even when their average global effect is small. Unlike added CO_2, which has a globally homogenous effect on radiation, changes in land cover and land management can produce large spatial variations in climate-system fluxes. Those variations are the driving forces disturbing local and regional weather patterns.

The weather effects are all the more concerning because they are often spatially coherent over large scales. The alteration of land at one location may influence weather patterns at distant locales through atmospheric couplings known as teleconnections.

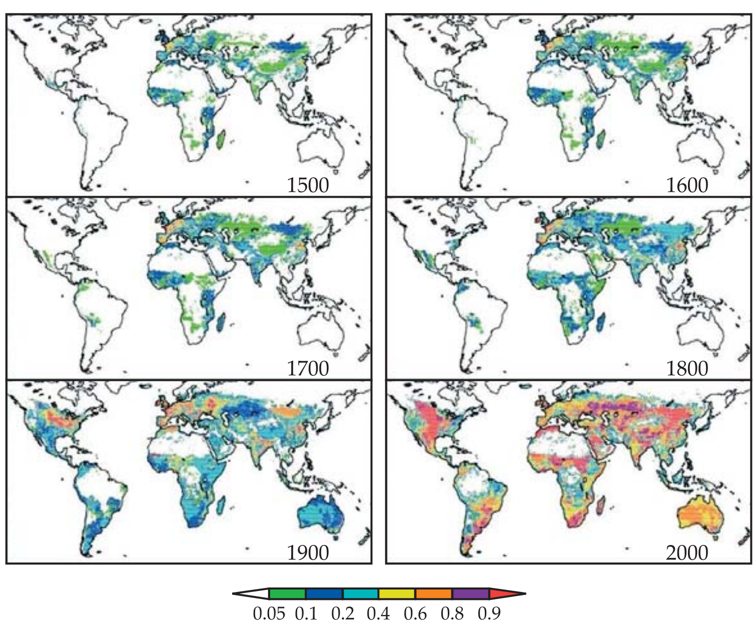


FIGURE 3. EARTH'S NATURAL LANDSCAPE has been increasingly converted to cropland and pasture over the past 500 years. The color key gives the local relative fraction of land converted to agricultural use. The analysis techniques used to create the map continue to undergo refinement. For example, in Australia too much landscape is shown as pasture. (Adapted from ref. 5.)

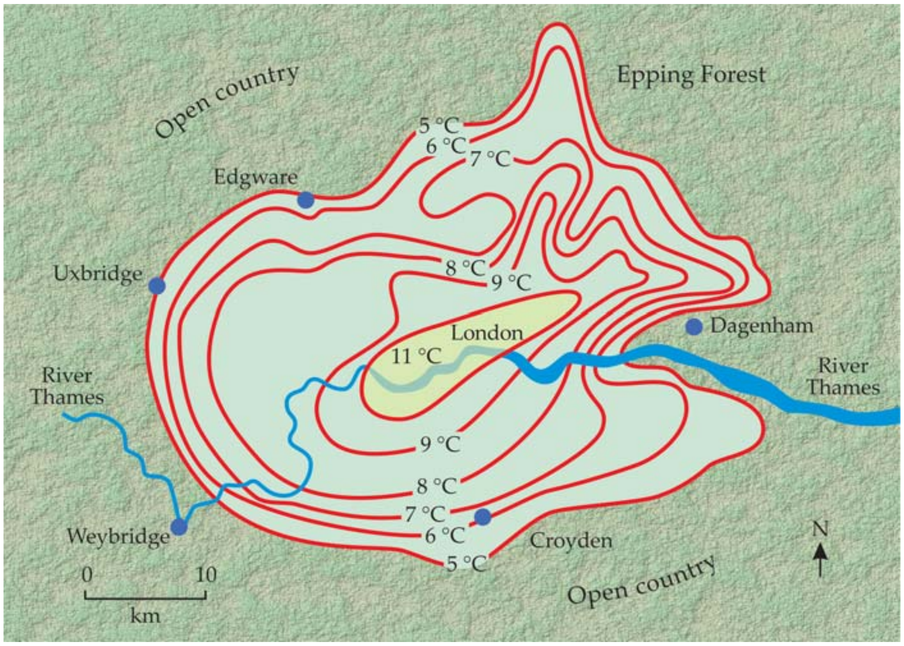


FIGURE 4. THE URBAN HEAT-ISLAND EFFECT, driven largely by the replacement of forests with roads and buildings, gives rise to temperatures in London that are as much as 6 °C warmer than those in the surrounding open country. Shown here are the low temperatures on a typical day in May. (Adapted from ref. 18.)

The hypothesized mechanism is analogous to that by which El Niño, the periodic warming of the eastern and central Pacific Ocean, affects weather thousands of kilometers away. Although the theory is still being explored, teleconnections are thought to link land use to changes in the polar jet stream, the paths of tropical cyclones, and the frequencies and intensities of droughts, floods, heat waves, and other weather events.

The Land Use Model Intercomparison Project, led by David Lawrence of the National Center for Atmospheric Research and George Hurtt of the University of Maryland, is one of several current efforts to improve our understanding of teleconnections and land's role in the climate system. The researchers are urging modeling groups to examine those and other issues of land-related climate forcings.

A matter of perspective

In 2009, 19 fellows of the American Geophysical Union concluded that

> in addition to greenhouse gas emissions, other first-order human climate forcings are important to understanding the future behavior of Earth's climate. These forcings are spatially heterogeneous and include the effect of aerosols on clouds and associated precipitation, the influence of aerosol deposition . . . and reactive nitrogen, and the role of changes in land use/land cover. Among their effects is their role in altering atmospheric and ocean circulation features away from what they would be in the natural climate system. As with CO_2, the lengths of time that they affect the climate are estimated to be on multidecadal time scales and longer.[12]

A few years later, scientists at the University of New South Wales made the case that the human influence on extreme temperatures cannot be assessed by CO_2 levels alone because at the regional scale, land cover and land management can enhance or mask effects from greenhouse gases.[13] Also, global averaging tends to obscure land-change effects, which can depend on geographical region, latitude, and the previous state of the landscape. Yet anthropogenic greenhouse gas emissions have remained the primary focus of multidecadal climate models such as those that informed the debate that resulted in the 2015 Paris agreement.

However, are CO_2 levels and global averaged surface temperature sufficient to generate accurate and meaningful forecasts? Two leading hypotheses have emerged.

The first argues that the accuracy of climate forecasts emerges only at time periods beyond a decade, when greenhouse gas emissions dominate over other human forcings, natural variability, and influences of initial value conditions. The hypothesis assumes that changes in climate are dominated by atmospheric emissions of greenhouse gases, of which CO_2 is the most important. It represents the current stance of the Intergovernmental Panel on Climate Change and was adopted as the basis of the Paris agreement.

A second hypothesis is that multidecadal forecasts incorporating detailed initial value conditions and regional variation set an upper bound on the accuracy of climate projections based primarily on greenhouse gas emissions. According to that view, successful models must account for all important human forcings—including land surface change and management—and accurately treat natural climate variations on multidecadal time scales. Those requirements significantly complicate the task of prediction.[14]

Testing the hypotheses must be accomplished by using "hindcast" simulations that attempt to reproduce past climate behavior over multidecadal time scales. The simulations should be assessed by their ability to predict not just globally averaged metrics but changes in atmospheric and ocean circulation patterns and other regional phenomena.

Reframing risk

The climate system and our role in it are complex. Not only is climate influenced by human forcings, but those forcings are influenced by a host of societal and environmental factors, including population growth, personal consumption levels, and property-value trends. (See the article by Paul Higgins, PHYSICS TODAY, October 2014, page 32.) How then should we assess vulnerabilities and mitigate risks of future climate change?

In our view, the approach should be a comprehensive one that accounts for the full range of forcings, not just carbon emissions. It should incorporate risks from human modification of the land, including the effect of land use on weather patterns.[14] And it should adopt a resource-based vulnerability framework: Identify climate, environmental, and societal threats to critical water, food, health, energy, and ecosystem resources; then optimize mitigation and adaptation strategies according to the relative risks of the various threats to each resource. (See figure 5.)

In the American Geophysical Union's 2012 monograph on extreme events and natural hazards, several scientists—including one of us (Pielke)—recommended a resource-based framework focused on local and regional scales as a more inclusive approach for policymaking.[15] Compared with conventional approaches, which start from the global-climate-model perspective, resource-based frameworks are better equipped to deal with the diversity and complexity of societal and environmental threats faced at the community level.

A resource-based vulnerability framework would give policymakers a better perspective not only of how human forcings affect climate but of how climate affects risk. For example, restricting development of land in flood plains and in coastal locations affected by hurricane storm surge is an effective adaptation strategy regardless of how climate changes.

At present, land is being considered too narrowly in the development of climate policy. To help reduce unintended impacts of land use on climate, we recommend the following:[16]

▶ Translating international treaties and protocols into national policies and actions that deliver positive climate outcomes and reduce the spectrum of risks to key societal and environmental resources.

▶ Updating international protocols to reflect new scientific understanding of the role of land in the climate system.

▶ Continuing to invest in the measurement, database development, reporting, and verification of land-use and land-management activities while monitoring effects of those activities on the climate system and linking them to emissions-reduction efforts.

▶ Adding developed countries to the Reducing Emissions from Deforestation and Forest Degradation protocol, which currently covers only developing countries.

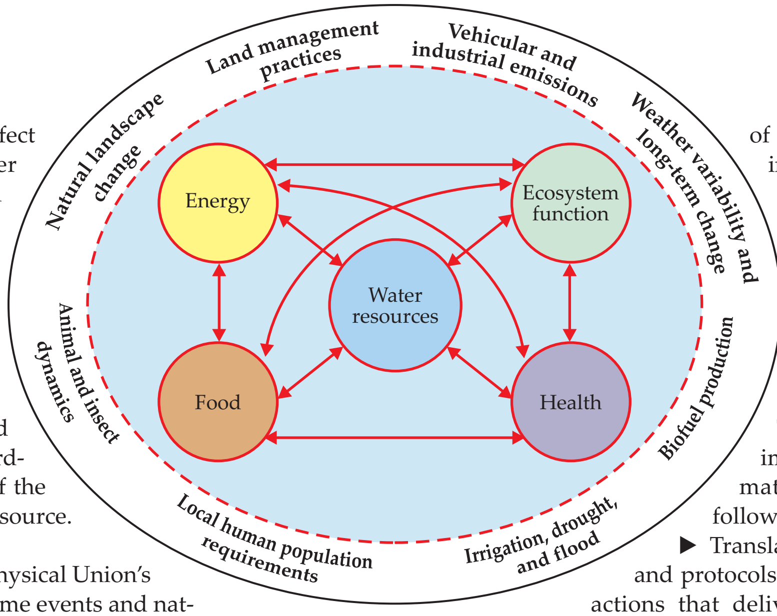
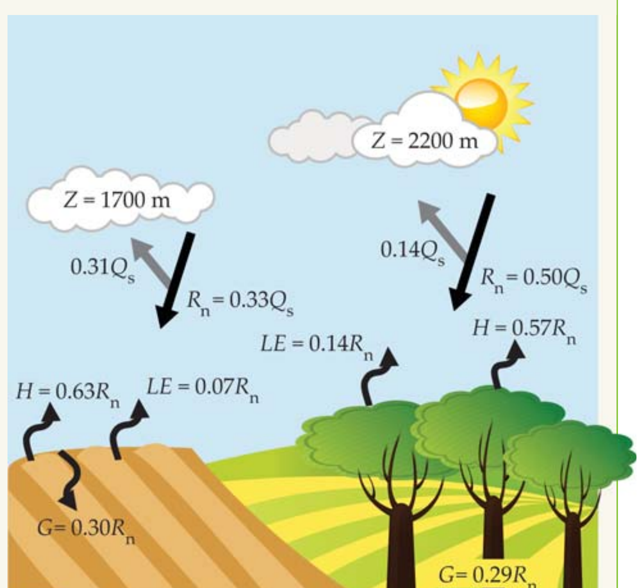


FIGURE 5. VULNERABILITIES TO CLIMATE CHANGE can be assessed within a resource-based framework like the one illustrated here, which shows environmental, societal, and climate risks to water resources. The various factors in the outer ring illustrate stresses on the water supply, which, in turn, is interconnected with other key resources, including food, energy, human health, and the ecosystem. (Adapted from ref. 14.)

DEFORESTATION DOWN UNDER



Southwest Australia's landscape has changed drastically over the past several decades, with approximately 13 million hectares of native vegetation cleared for agricultural use. In a series of field campaigns named the Bunny Fence Experiment, Tom Lyons (Murdoch University, Perth, Australia), Udaysankar Nair (University of Alabama in Huntsville), and their coworkers assessed the impact of the terrestrial makeover on the region's climate. The team determined representative midday values of sensible-heat (H), latent-heat (LE) fluxes, net radiation (R_n), solar radiation (Q_s), and ground conduction (G) for the two land surface conditions. The gray arrows indicate reflected solar radiation.

Due to its darker albedo, the vegetated landscapes absorb more—and reflect less—radiation from the overlying atmosphere. As a result, the top of the atmospheric boundary layer (Z), where cumulus clouds typically form, is higher over wooded areas. Woodlands also release more of their energy into the atmosphere in the form of latent heat. Those differences can affect weather and climate phenomena deeper into the atmosphere.

Land-use changes in southwest Australia have altered not only heat and moisture fluxes but surface temperatures, humidity, and fluxes of trace gases and aerosols. The region is by no means an outlier: Take a flight across virtually any country—for example, from Washington, DC, to Denver, Colorado, in the US—and the human footprint on the landscape is plainly evident in the many cities, towns, and farms that pass below.

Earth's future at the fore

As Earth's population has boomed, human forcings have become an increasingly important driver of climate. Current climate-change mitigation policies do not sufficiently incorporate the effects of changes in land surface and land management on the surface albedo, the fluxes of heat and moisture in the atmosphere, and the distribution of energy within the climate system.[17] Given the goal of mitigating climate change at local, regional, and global scales, it won't suffice to frame the problem simply in terms of greenhouse-gas-induced warming; one must consider threats posed by the entire climate system—and work toward a fuller understanding of that system.

To be sure, incorporating land-cover change and land management complicates attempts to address climate change through, say, a system of credits and debits such as those being considered for fossil-fuel emissions and carbon sequestration. However, recognition of the complexity of anthropogenic climate change does not absolve us of the responsibilities to understand and minimize our impact on Earth's climate system and to reduce societal and ecological vulnerability to environmental change of all types. The problem is formidable, but so are the tools, technologies, and resources with which we can tackle it.

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