the limited cycle life of batteries (generally several hundred to a few thousand cycles), compared to demonstrated full charge-discharge cycles for ECs into the many millions. The major differences between rechargeable (secondary) batteries and ECs, and their important fundamental properties, are compared in the table.

An important related class of energy storage devices are pseudocapacitors, which undergo electron transfer reactions but behave like capacitors. These materials store energy through highly reversible surface redox (faradic) reactions in addition to the electric double-layer storage. Materials that exhibit such pseudocapacitive storage (*1*) range from conducting polymers to a variety of transition metal oxides (*3*–*5*). The RuO$_2$ pseudocapacitor has the highest specific capacitance (~1000 F/g) in this class, but is prohibitive in price (a vehicle-sized EC of RuO$_2$ would cost more than $1 million). Efforts to develop more practical pseudocapacitive materials are now quite active.

The second generation of ECs used symmetric designs and organic electrolytes—typically an ammonium salt dissolved in an organic solvent such as propylene carbonate—which increased the rated cell voltage from under 1 V to ~2.5 V per cell. The most recent EC designs, which date from Russian patents in the mid-1990s, are asymmetric. One electrode is identical to those used in symmetric ECs, whereas the other is battery-like (relying on electron charge transfer reactions) but has much greater capacity and higher operating voltage. Asymmetric capacitors with specific energies of >10 watts-hour/kg are commercially available (*6*) and are well suited for transportation (traction) applications. Charging times for such systems are ~10 min.

Several asymmetric EC designs under development (*7*–*9*) use a lithium-ion intercalation electrode with an activated carbon electrode in an organic electrolyte (*7*) or an activated carbon electrode with a lead dioxide battery-like electrode and sulfuric acid as the electrolyte, with the potential of specific energies in excess of 20 watts-hour/kg at very low cost (*8*). Each of these designs can provide high cycle life relative to that of a battery because of the electrode capacity asymmetry. Capacity asymmetry reduces the depth of discharge of the battery-like electrode, thereby increasing its cycle life and power performance.

Symmetric ECs with specific energies of ~5 watts-hour/kg and response times of 1 s are widely available and can be used to store and release regenerative braking energy efficiently in vehicles and industrial equipment. They can also be used for load leveling—delivering power above the average value provided by a distributed generator (such as a fuel cell) and storing excess energy when power levels are below average.

Although lithium-ion batteries have advanced greatly in recent years, they still require 3 to 5 min for charging, versus ~1 s for an EC. Thus, battery systems generally must be grossly oversized in such applications to improve their efficiency and to lengthen their cycle life. Also, ECs are generally much safer than batteries during high-rate charge and discharge.

Finally, ECs are being used across a vast swath of commercial and industrial equipment. One example is a seaport rubber-tired gantry crane (see the figure) that has a capacitor system to store energy during load lowering. The use of ECs has reduced its energy usage by 40%.

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CLIMATE CHANGE

Ecosystem Disturbance, Carbon, and Climate

Steven W. Running

Models of climate change effects should incorporate land-use changes and episodic disturbances such as fires and insect epidemics.

The terrestrial carbon cycle provides a sink for about 25% of the anthropogenic carbon emissions that increase atmospheric CO$_2$. Comprehensive models based on a detailed understanding of this carbon sink are needed to inform mitigation strategies aimed at stabilizing climate and adaptation strategies to minimize biospheric impacts. Can current models represent the full global range of ecosystem dynamics and both interannual and episodic variabilities that determine the strength of the terrestrial sink?

In early global climate models, or general circulation models (GCMs), the land surface was merely a necessary boundary condition influencing momentum dissipation, energy balance, and moisture content of the atmosphere. In 1983, Robert Dickinson was the first to explicitly represent the biophysics of ecosystems in a GCM. The next generation of land models in GCMs—used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (*1*)—incorporated biogeochemical principles of ecosystems, notably the carbon cycle and vegetation controls on the water cycle. Photosynthesis was explicitly computed from principles grounded in cellular biochemistry, with important sensitivity to changing atmospheric CO$_2$. Ecosystem releases of CO$_2$ from plant respiration and decomposition of dead material were incorporated in the models to complete land carbon balances.

Yet, a recent intercomparison illuminated a distressing disagreement of 11 land models attempting to simulate future atmospheric CO$_2$ with interactive terrestrial carbon balances (*2*). Some models predicted dramatic enhancements in photosynthesis for a doubled-CO$_2$ atmosphere, whereas others computed enhanced respiration and decomposition from the higher temperatures. The model responses of annual net primary production (NPP) for a doubled-CO$_2$ atmosphere ranged from near zero to 60%, with the average response about 40%. However, none of these models had nitrogen limitations.

To allow more confidence in future simulations, field programs are being used to improve these land models. For example, the

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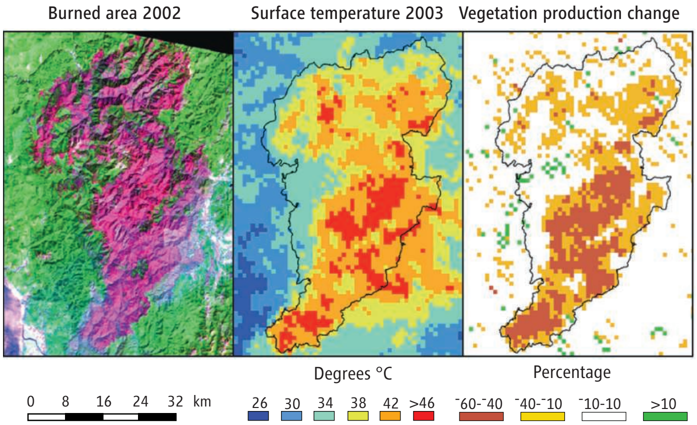
FLUXNET global network of eddy-covariance flux towers provides full daily and seasonal cycles of net ecosystem carbon flux in multiple biome types and climates worldwide. Testing the NCAR Community Land Model against carbon and water flux data from 15 diverse FLUXNET sites revealed a need for improved water balance calculations that can simulate soil water deficits more accurately and highlighted nitrogen limitations on photosynthetic capacity (*3*). Combining seasonal eddy flux data, satellite greenness index data, and atmospheric CO$_2$ concentration data has illustrated some surprising carbon cycle feedbacks. Warming temperatures in the Northern Hemisphere have lengthened frost-free growing seasons and favor enhanced photosynthesis in the spring, but also enhanced respiration in the autumn, virtually canceling out any net gain in the annual terrestrial carbon sink (*4*). Land models must accurately represent this intricate seasonal balance between photosynthesis and respiration.



Impact of fire disturbance on land surface energy and carbon balances. In the summer of 2002, the Biscuit Fire in Oregon destroyed 2000 km^2 of temperate evergreen forests (**left**). A Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image taken on 28 July 2003 (**middle**) shows land surface radiometric temperatures of 46° to 50°C in the area burned the summer before, whereas temperatures in the adjacent unburned forests range from 27° to 32°C. Annual vegetation production measured from MODIS (*4*) (**right**) was 20 to 60% lower in the burned area in 2003 to 2004 than before the wildfire.

The latest challenge is to expand flux tower–based measurements to global scales across the full range of biomes and climates. Currently, the only terrestrial carbon flux variable measured globally on a regular basis is NPP (*5*). A new modeling test, C-LAMP (Carbon Land Model Intercomparison Project), compares annual NPP from the current-generation GCM land models with global satellite derived NPP; correlations of 0.85 to 0.91 clearly show the models are improving (*6*).

A recent FLUXNET synthesis found that disturbance was the primary mechanism that changes ecosystems from carbon sinks to sources (*7*). Disturbances like fire change the energy, water, and carbon balances of a land surface dramatically and often instantly. In tropical areas, cropland and grazing fields are burned annually to clear away unwanted plant debris and stimulate new plant growth. A fire first releases a pulse of carbon and then reduces the albedo of a surface from 15 to 20% to around 4% (*8*). The blackened surface absorbs much more incident solar energy, and with little live vegetation remaining for evaporative cooling, midday surface temperatures can easily reach 50°C (see the figure). Albedo may recover from resprouting vegetation within a few months in a tropical grassland, but require decades in a boreal forest. Global fires burn an estimated 3.0 to 4.5 million km^2 per year—about 4% of vegetated land surfaces—and emit 2 to 3 Pg of carbon into the atmosphere annually, equivalent to 30% of fossil-fuel emissions (*9*). A recent analysis of accelerating wildfire trends completely reversed the earlier expectation that Canadian forests would be a future net carbon sink as warming temperatures extend the boreal growing season (*10*).

Less extreme disturbances like windstorms or insect epidemics do not change the surface albedo dramatically but shift trees from live carbon sinks to dead and slowly decaying carbon sources over substantial areas. In 2005, Hurricane Katrina killed an estimated 320 million trees in the southeastern United States; these trees became a carbon source of about 0.1 Pg, nullifying the entire annual terrestrial carbon sink of the rest of U.S. forests for that year (*11*). An unprecedented mountain pine beetle epidemic in western North America that started in 1999 in British Columbia is flipping an estimated 470,000 km^2 of forest land from a small annual carbon sink to a nearly equivalent carbon source from dead trees that will decompose over decades (*12*, *13*). Current land models cannot recreate such episodic ecosystem disturbances mechanistically with proper climatic triggers, and no systematic global monitoring of disturbance exists, although prototypes are under development (*14*).

The next generation of GCMs must additionally represent the human-driven biogeographical dynamics of land cover and land-use change through urbanization, agricultural land conversion and grazing, deforestation, episodic disturbances, and the feedback responses of these processes to the atmosphere. According to current satellite-based estimates, 17 million km^2, or 14% of the land surface, has been changed by human agricultural activity, and another 28% is used for domestic animal grazing (*15*). Every year, new human land-use activities are adding 1.1 Pg of carbon to the atmosphere, in addition to the 8 Pg per year of fossil fuel carbon emissions; this trend will probably accelerate with growing population (*16*). GCM runs can be initialized with satellite data sets of existing land cover, but must then simulate both future climates and changing land-use patterns.

It is unlikely that all these new ecosystem details can be added to the land models of leading GCMs in time for the IPCC Fifth Assessment simulations that are expected to start within the next 2 years. Predicting specific disturbance events is not necessary for global science; regional average occurrence rates should suffice. The GCMs must then represent the pulse of carbon emission and subsequent recovery in ecosystem biogeochemistry, and the probabilities of extreme climatic events that trigger these disturbances. The most socially important question is whether these disturbance rates will increase in the future.

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