### About this issue

Our Nation’s communities, natural resources, energy security, and infrastructure can be affected in complex ways by changes in land use, climate, and other factors. Developing sustainable management strategies requires a firm base of scientific evidence, and the USGS Land Change Science Program supports multidisciplinary research to understand the processes that influence the Earth system.

### Science Highlights

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News from the USGS Land Change Science Program

Volume 8, Spring 2019

About this issue

This issue of Earth Science Matters highlights recently published research that contribute to an improved understanding of how changing land use, climate, and environment affect communities, ecosystems, and the services they provide.

These include:

- What are the effects of grazing on desert systems?
- What are the relative contributions of climate variability vs human activity to wildfire in the West?
- How do changes in land use and climate affect storage of carbon in coastal and terrestrial ecosystems?
- What was the natural frequency and extent of droughts across North America, and how did they affect critical ecosystems?
- What is the natural variability of ocean temperature and circulation, and how does it influence Arctic climate?
- How can recent studies of giant sequoia vulnerability to drought be used to inform forest management strategies?

Data generated by these studies provide real-world evidence needed to test and develop models to project changes under different land use and climate scenarios.

Earth Science Matters includes a sampling of the multidisciplinary research conducted by the Land Change Science Program to provide data and improve understanding on the rates, patterns, and consequences of changing environment, climate, and land use. We welcome comments and feedback to shape future issues. If you would like to subscribe to future issues, please click the “Subscribe” button on the Program Newsletter page.

Debra Willard
Coordinator, Land Change Science Program
Tracking long term changes in lake levels within permafrost regions of Alaska

Lakes in permafrost (frozen ground) across arctic and sub-arctic regions provide habitat for waterfowl, offer productive breeding areas, promote aquatic production, and play key roles in cycling of nutrients and water. As such, they have regional to global implications for ecosystems, carbon, wildlife, and infrastructure. Lakes formed from thawing permafrost (thermokarst lakes) have been an agent of landscape change for millennia, and their evolution reflects the complex interplay of climate, vegetation, hydrology, and fire.

Between the late 1980s and 2014, sustained thermokarst lake-level declines occurred in Alaska’s Yukon Flats National Wildlife Refuge, raising questions about the significance of persistent lake level declines, their relationship to precipitation and temperature trends, and the subsequent effects on the region’s highly productive waterfowl breeding habitat. The lake level declines reversed within a 13-month period from 2015 to 2016, when higher-than-average precipitation resulted in the recovery by most lakes to maximum levels, including two intensive study sites. These high levels persisted at least through the summer of 2018. Instrumental measurements of lake level are limited so there are no data prior to the early 1950s to indicate whether such extreme lake-level variations are typical for Yukon Flats thermokarst lakes.

Scientists from the USGS and Idaho State University set out to document changes in thermokarst lake-level dynamics over decades, centuries, and millennia by sampling lake water and sediment cores. By combining modern observations with high-resolution records of past lake-level change, the researchers are placing recent extremes into a longer-term context and providing new insights on how lake levels in Alaska may evolve in the future.

Estimates of past precipitation and evaporation within lakes can be made from geochemical signatures contained in the minerals of their sedimentary deposits. One such signature, the oxygen isotope ratio, compares the abundance of two stable oxygen isotopes in carbonate: $^{18}\text{O}$ and $^{16}\text{O}$. In lakes that lose significant amounts of water by evaporation, the
lighter $^{16}\text{O}$ isotope is lost in evaporated water molecules so that the remaining lake water has more of the heavier $^{18}\text{O}$ isotope. Therefore, higher ratios reflect more evaporation relative to precipitation, such as in drier periods, whereas lower ratios record less evaporation and a wetter climate.

The oxygen isotope record of past lake water is preserved layer-by-layer within lake sediment minerals, and measurement on incremental samples provided continuous records of past hydroclimate from two lakes, Track Lake and Twelvemile Lake. The Track Lake record spans the past ~5,000 years and indicates that high-magnitude lake-level variations had frequently occurred on multi-annual to decadal time scales before the observational period. Such extremes are persistent hydroclimatic features of the Yukon Flats region. This study shows that by framing recent lake-level fluctuations within a longer-term context, we can more confidently identify the occurrence of abnormally sustained trends, which provides essential insight to future impacts on high-latitude wetland ecosystems, permafrost, and carbon.

The paper “Lake levels in a discontinuous permafrost landscape: Late Holocene variations inferred from sediment oxygen isotopes, Yukon Flats, Alaska” was published in *Arctic, Antarctic, and Alpine Research* and is available here: [https://www.tandfonline.com/doi/abs/10.1080/15230430.2018.1496565](https://www.tandfonline.com/doi/abs/10.1080/15230430.2018.1496565)
Domestic livestock grazing is the most widespread land-use type in moisture-limited ecosystems (drylands) globally, including the Colorado Plateau. Livestock grazing, especially overgrazing, in drylands can negatively affect plant communities, biological soil crusts (lichens, mosses, and cyanobacteria growing on the soil surface), and soils. This can have multiple impacts including increased occurrence of undesirable nonnative plant species, dramatic changes in plant community, increased erosion, and increased runoff. Understanding the consequences of grazing can provide useful information on how to better manage livestock in the future, as well as restore damaged dryland systems. Studies of long-term grazing experiments are particularly useful in understanding grazing and its ecological impacts.

In 1953, a Federal research group established four paired watersheds in western Colorado, USA to study how grazing by domestic livestock affected runoff and sediment yield. Exclusion of livestock from half of the watersheds dramatically reduced runoff and sediment yield after the first 10 years, primarily due to changes in ground cover (biological soil crusts, plant litter); there was no observable change in vegetation.
In a recent study, USGS scientists and researchers from Colorado Mesa University, reported the results of repeated soil and vegetation assessments after more than 50 years of grazing exclusion. Within each watershed, six to thirteen 30-m long transects were established in 2004 for sampling. Results show that many of the differences in soil conditions between grazed and ungrazed watersheds observed in the 1950s and 1960s were still present in 2004, despite a reduction in the numbers of livestock over the years.

Overall, vegetation remained similar between grazed and ungrazed areas; where plants did respond to grazing, those responses depended on the soil type. For example, on one of the three soil types in the watersheds, grazing increased the frequency of cheatgrass (an aggressive nonnative grass), but not on the other two soil types.

Soil conditions in the grazed watersheds differed from ungrazed areas, with decreased soil lichen abundance and soil stability, increased soil compaction, and the occurrence of physical crusts at the soil surface. Comparisons of ground cover measured in 2004 to those measured in 1953, 1966, and 1972 suggest that many of the differences between grazed and ungrazed watersheds were likely driven by high sheep numbers grazing during 1950s drought years.

These persistent differences in watershed soil conditions, despite large reductions in livestock use, suggest the combination of overgrazing and drought may have pushed these salt desert ecosystems into a persistent, degraded ecological state. The results of this study support many current assessment and monitoring approaches that include a focus on plants and soil quality indicators to evaluate rangeland condition.

The paper “Insights from Long-Term Ungrazed and Grazed Watersheds in a Salt Desert Colorado Plateau Ecosystem” was published in Rangeland Ecology & Management and is available here: https://www.sciencedirect.com/science/article/pii/S1550742418300320.
Wildfire is a major source of ecosystem disturbance with increasingly wide-ranging effects on society. The occurrence and distribution of wildfires are controlled by the state of fuels in burnable biomes, atmospheric circulation, energy and water balances of the Earth’s surface, land use and land use change, and fire suppression. USGS scientists and colleagues from the University of Oregon compiled a new fire dataset and combined it with regional climate simulations to investigate the association of wildfire with the seasonal cycle and interannual climate variability. This effort is a product of a longer-term USGS project that combines data analysis and modeling to improve understanding of how changing land use and climate affect the Earth system over a wide range of temporal and spatial scales.

The study used the regional climate model, RegCM3, to provide high-resolution, continuous, internally consistent climate fields over a 50 x 50 km grid covering most of North America, along with four 15 x 15 km grids covering most of the West (Figure 1). Joint analysis of wildfire data and RegCM3 simulations diagnosed interactions and feedbacks among atmospheric circulation, surface climate, energy balance, and soil moisture, along with their controls on wildfire.

The daily fire dataset (date, point of origin, and ultimate size) combined data from United States and Canada from 1986 to 2013. The dataset contains over 2 million wildfires from all ignition sources that burned more than 100 million hectares over the period (see Figure 1). The daily data were aggregated into monthly totals and the RegCM3 grid cells.

Lightning-set fires amount to 24-56% of the total number of fires and 66-82% of the total burned area in the four domains in the western US. Although wildfires occur throughout the year, fire activity increases in the Southwest and boreal forest in April and peaks May through August, when lightning from thunderstorms is common. Fall through spring, fires set by non-lightning ignition sources are found primarily over the south, southeast, and Florida. Human-set fires extend the fire season into months and areas in which climate conditions are not otherwise conducive to fire.

The model runs clearly illustrate the association of wildfire with the seasonal climate cycle and how wildfire occurrence is influenced by variability in mid-tropospheric circulation, receipts...
of solar radiation, precipitation, surface energy balance, and soil moisture (Figure 2). Furthermore, the analysis differentiates the response of North American wildfire to warm and cold phases of El Niño–Southern Oscillation events. During El Niño, wet conditions from the Southwest across the Gulf suppressed fire activity while early season fire activity was enhanced during warm, dry La Niña events in these regions.

![Figure 2: March through September composite anomalies for net radiation (B) and soil moisture (H) for high fire years (first row) and low fire years (bottom row) in the Northern Rockies 15-km domain. The colored anomaly maps are overlaid with the area burned by lightning and human and unknown ignition sources. The composite anomalies are computed by subtracting the 1986-2013 average from the average of the 9 highest (lowest) fire years.](image)

This modeling approach can be extended to test hypotheses and investigate paleo and future climate-wildfire interactions under differing climates and vegetation distributions. Additionally, it may inform wildfire potential and hazard models that are used to characterize seasonal wildfire outlook assessments.

Tides can reach far inland along rivers throughout the southeastern United States and elsewhere in the world. Where a combination of tides and flows from upstream cause water levels to rise higher than the river banks, tidal wetlands form, often in freshwater environments. These upstream freshwater wetlands grade into low salinity marshes closer to the ocean, where considerable wetland area can form. Carbon stored in tidal freshwater forested wetlands, tidal freshwater marshes, and even low-salinity marshes are not commonly included within the burgeoning field of blue carbon science. “Blue Carbon” typically refers to ocean-sourced carbon stores but this concept has recently started to include tidally-influenced wetlands; e.g., mangroves, salt marshes, and sea grasses. The US has considerable tidal freshwater wetland area for inclusion as well.

In a recent paper, USGS scientists and researchers at Clemson University reported results from more than a decade of research along two Atlantic coastal tidal rivers (the Waccamaw and Savannah Rivers) to quantify the carbon standing stocks (total amount of carbon stored in the ecosystem). Among the study sites are tidal freshwater forested wetlands, transitional forest/marsh, and marshes that range from freshwater to low salinity. Using long-term study plots, the scientists quantified the total carbon entering the sites through primary productivity and sedimentation as well as all of the carbon exiting the sites through decomposition, greenhouse gas losses, and lateral fluxes of dissolved carbon. Finally, long-term soil carbon burial was described over different Holocene time periods, ranging from 144 to 4346 years before present. Thus, full carbon budgets were developed for each site under study.

Carbon standing stocks ranged from 322-1264 Mg C/hectare, with higher values (>1100 Mg C/hectare) surpassed only by the carbon storage potential of a few tropical mangrove forests. Accordingly, annual mass balance of carbon (all carbon entering versus all carbon exiting the ecosystem) was high for all sites, indicating that these ecosystems are
The paper, “The role of the upper tidal estuary in wetland blue carbon storage and flux”, was published in Global Biogeochemical Cycles and is available here: https://doi.org/10.1029/2018GB005897
Unraveling the impacts of North Pacific and North Atlantic Ocean warming on Arctic climate

The Arctic is one of the world’s most sensitive regions to climate change, where temperatures typically change three times more than the global average in response to a given (radiative) climate forcing (an effect known as Arctic amplification). This makes the Arctic particularly susceptible to rapid perturbations in both physical and ecological systems. In recent years, the Arctic has experienced record-breaking warming and sea-ice retreat that have exceeded climate model predictions, making it essential to unravel the mechanisms underpinning this acceleration.

Paleoclimate records preserved in deep-sea sediments and ice cores show that abrupt temperature changes in the Arctic occurred at the same time as rapid changes in sea surface temperature in the high-latitude North Pacific and North Atlantic, hinting at strong links between subpolar ocean change and rapid Arctic climate change. However, these observations alone do not provide a way to parse the distinct contributions of regional ocean warming on Arctic change.

Previous research has largely focused on the role of North Atlantic Ocean circulation changes in abrupt Arctic climate fluctuations with the assumption that a stronger deep-water formation in the North Atlantic was responsible for rapid warming events in the Arctic. However, unprecedented warming of the North Pacific between 2014-2016 was accompanied by record-breaking Arctic warming, despite a weakening of North Atlantic circulation and relatively ‘cool’ sea surface temperature in the subpolar North Atlantic (Figure 1). This highlights uncertainty in how sea surface temperature in the North Pacific and North Atlantic may affect Arctic climate processes differently.

Researchers from the USGS and the Carnegie Institution for

Figure 1. Surface air temperature anomaly (°C) between 2014-2016 relative to 1890-1970. Record-breaking warming in the Arctic occurred in conjunction with anomalous warming in the Northeast Pacific, despite anomalously cool sea surface temperatures in the North Atlantic. Continents are outlined in white. Data was accessed from NASA GISS Surface Temperature Analysis (GISTEMP). Source for historical temperature data: NOAA/NCEI’s Extended Reconstructed Sea Surface Temperature (ERSST) v.5 and Global Historical Climatology Network (GHCN) v.3.
Science set out to investigate whether remote temperature changes in the North Pacific and North Atlantic impact the Arctic in distinct ways. They used a global climate model (the Community Earth System Model from the National Center for Atmospheric Research) to modify the ocean-to-atmosphere heat transfer in regions of the North Atlantic and North Pacific Oceans to see how warming and cooling in each region affects Northern Hemisphere climate.

The resulting simulations showed that the Arctic was more sensitive to changes in ocean heat flux from the North Pacific than from the same latitude in the North Atlantic. This effect was primarily linked to a larger net moisture transfer (and accompanying latent heat flux) into the Arctic region in response to North Pacific warming. The larger moisture flux was associated with an increase in the formation of low-altitude clouds in the Arctic, which act as insulation to trap surface warmth and keep it from dissipating. The surface warming effect of these low-clouds thus accelerates the loss of sea-ice and amplifies ice-albedo feedback. This feedback causes retreating sea ice to further enhance surface warming through increased solar radiation absorption as highly reflective ice (high albedo) is replaced with darker (lower albedo) waters. Both processes act in concert to magnify the Arctic amplification effect.

These results highlight the central role that moisture flux into the Arctic plays in the feedbacks involved in Arctic amplification and casts new light on links between Pacific Ocean variability and Arctic change, providing insight into mechanisms that may accelerate Arctic warming in the future. Analysis of recent Arctic variability appears to corroborate the link between moisture intrusions (storms), enhanced low clouds, and accelerated sea-ice retreat.

While this study provides a first step in describing broad-scale differences in North Pacific and North Atlantic warming, further work is needed to understand how more complex modes of oceanic variability (such as the El Nino Southern Oscillation) manifest in the Arctic.

The paper, “Global and Arctic climate sensitivity enhanced by changes in North Pacific heat flux” was published in *Nature Communications* and is available here: [https://www.nature.com/articles/s41467-018-05337-8](https://www.nature.com/articles/s41467-018-05337-8)
New method to reconstruct winter ocean temperatures of the past

As average global temperatures change, the effects differ among locations and from season to season. While some locations see increased winter and summer temperature extremes, others may experience very little change in temperature, but large shifts in precipitation. To accurately project future changes in seasonality, we need to improve our understanding of how seasonality changed during past climate shifts in Earth’s history.

Scientists reconstruct seasonal and annual patterns of climate using paleoclimate proxies. In ocean sediments, these proxies include the remnants of microscopic organisms such as foraminifera, coccolithophorids and diatoms that lived in the surface ocean and are preserved in ocean sediments when they die and sink to the seafloor. Modern observations of these organisms in the ocean show that some species have well-defined differences in seasonal preference. Researchers from the USGS have developed a method to reconstruct winter temperatures in the ocean surface using a species of

![Diagram showing depth profile and temperature profiles](image-url)
foraminifera that grows almost exclusively during the winter. This advance allows paleoceanographers to reconstruct records of wintertime surface temperature extending back tens of thousands of years in the geologic record.

USGS scientists conduct research on planktic foraminifera, single-celled organisms living in the open ocean that build shells out of calcium carbonate. In addition to being a critical sink for atmospheric carbon, planktic foraminifera provide a means for paleoclimate researchers to document past changes in ocean temperature and salinity. The USGS deployed a sediment trap in the Gulf of Mexico to better define the depth and seasonal habitat of these geologically important organisms, as well as the factors that influence their chemical composition. The sediment trap, deployed since 2008, collects sinking particles in sample cups every 1–2 weeks. Those samples are recovered from the deep ocean every nine months and brought back to the lab to investigate the flux of different species of foraminifera (as well as other proxy recorders), and to analyze the chemical composition of their calcium carbonate shells.

One species of foraminifera, *Globorotalia truncatulinoides*, was found to have a very specific preference for winter conditions, with 92% of specimens living in January–March. *Globorotalia truncatulinoides* has traditionally been classified by paleoceanographers as a deep-dwelling species, preventing its use as a proxy for temperatures in the surface ocean. Using isotopic (d$^{18}$O and d$^{13}$C) and trace metal (Mg/Ca) analyses, USGS scientists demonstrated that one form (the non-encrusted form) of this species lives within the surface mixed-layer of the ocean. The trace-metal analyses were conducted using a technique called laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS). This approach allowed scientists to explicitly link the growth of primary calcium carbonate of the non-encrusted form of *G. truncatulinoides* to the surface ocean. Using this same technique, they were able to show that another form of this species (encrusted form) adds most of its calcium carbonate shell in deep water, below the thermocline, down to depths greater than 500 meters.

Ultimately, this study shows that when researchers avoid using specimens that have formed a crust, the Mg/Ca of the other (non-encrusted) species can be used to reconstruct winter sea surface temperature throughout the tropical and sub-tropical oceans, allowing scientists to reconstruct changes in seasonal climatic extremes in the geologic record.

This paper “Environmental controls on the geochemistry of *Globorotalia truncatulinoides* in the Gulf of Mexico: Implications for paleoceanographic reconstructions” was published in *Marine Micropaleontology*, and is available here: https://doi.org/10.1016/j.marmicro.2018.05.006
Investigating century-scale climate extremes across North America

Instrumental records of North American precipitation and temperature exist only for the last century or so, leaving significant uncertainty on natural patterns of variability over decadal and longer time scales. To improve our understanding of how North American water availability has varied over local to regional scales, USGS researchers have established a network of paleoclimate research sites to provide historical baselines for comparison to recent and future conditions. Members of this working group recently published the North American Hydroclimate Synthesis (NAHS), which summarizes the hydroclimate history of the last 2,000 years from 69 locations across the continent (Figure 1).

This initial study investigated the histories of wetter- and drier-than-average conditions (i.e. hydroclimate) at 69 locations to identify the natural ranges of hydroclimate variability at the century timescale. The study also determined whether there have been broad regional or continent-scale spatial patterns in hydroclimate during the past 2000 years. The collaborative effort by 22 USGS researchers is advancing our understanding of broad-scale patterns of past climate change to improve climate model capabilities and guide future paleoclimate studies through identification of critical spatial and temporal data gaps.

The NAHS is a multi-proxy atlas of 69 continental climate reconstructions based on previously published and peer-reviewed research. Working group members compiled paleoclimate information derived from geochemical, geophysical, and biological climate proxy data from lake sediments, caves, wetlands, and coastal marine environments. Based on these proxies, wetter- and drier-than-average periods were identified from each record. A uniform method to determine ages of samples was applied to each site, ultimately allowing comparison of different sites and proxies with statistical rigor.
By comparing NAHS with similar reconstructions of atmospheric temperature, the study indicated that many localities became drier during warmer centuries, particularly between 50 BCE (years before the Common Era, where 0 CE = 0 AD) and 450 CE and between 800 CE and 1100 CE (Figure 2). However, there was substantial variability among sites, and the patterns of drought differed between the two multi-century periods.

In general, the reconstruction revealed that large areas of the continent became dry for centuries at a time, while other areas tended to become wetter. Not only did many of these shifts persist for hundreds of years, but there were numerous fluctuations between wet, dry, and average conditions over the course of the last 2000 years in any given region. These findings are important, because they imply that widespread natural variations in hydroclimate at the centennial timescale have been a common trait of North American landscape history.

Interestingly, significant hydroclimate pattern transitions occurred out of sync with reconstructed mean temperature changes. Thus, while temperature may play a role in when and where century-scale shifts toward drier conditions occur, other factors are clearly involved. More research that incorporates additional paleoclimate proxy data and computer model simulations is needed in order to better understand the mechanisms that drove century-scale hydroclimate changes in the past, which is crucial information for predicting future trends and patterns of drought.

The paper, “A North American hydroclimate synthesis (NAHS) of the Common Era” was published in Global and Planetary Change and is available here: https://doi.org/10.1016/j.gloplacha.2017.12.025

Figure 2. Top: the decadal mean extra-tropical Northern Hemisphere temperature anomaly (red line) relative to the 1961–1990 mean and the two standard deviation error bars (light red shading; Ljungqvist, 2010). Bottom: the number of proxy data locations in North America that indicate wet, dry, and neutral century-scale hydroclimate states represented as the difference between the total number of wet and dry sites in the NAHS for 100-year window midpoints from 50 BCE to 1850 CE. Blue shading above “0” on the y-axis highlights the value range where more sites in the NAHS exhibited a wetter climate than the number of sites that exhibited a relatively drier climate, and brown shading below “0” in the y-axis highlights the value range where more sites exhibited a drier climate than a wetter climate. The cross-hatched areas indicate values that exceed one standard deviation from the means of both the thick gray line and the thin black line. The warm Roman Warm Period (RWP) and Medieval Climate Anomaly (MCA) are outlined in solid red lines, and the cool Dark Ages Cold Period (DACP) and Little Ice Age (LIA) are outlined in solid blue lines.
**Historical land-use change and ecosystem carbon balance in the continental United States**

Forests, grasslands, and shrublands absorb carbon dioxide from the atmosphere through photosynthesis in living plants and emit carbon dioxide back to the atmosphere through respiration by plants and soil decomposer organisms. When more carbon dioxide is absorbed than emitted back to the atmosphere, these ecosystems act as net carbon sinks. This provides an important climate benefit by partially offsetting human emissions of greenhouse gases. Within the United States, terrestrial ecosystems currently offset about 12% of human carbon dioxide emissions per year. However, estimates of the size of the U.S. land carbon sink vary widely, in large part because of uncertainties surrounding the long-term impact of changes in land use and land cover.

![Net Biome Productivity](image)

*Figure 1.* In panel a, bars show the net biome productivity (NBP) for the conterminous United States by LULC class for the period 1973–2010. Points and error bars show the total NBP across the conterminous US with 95% Monte Carlo confidence intervals. The dotted line plots the mean annual NBP of 254 Tg C yr⁻¹. The solid line plots the linear trend over the time series. In panel b, the solid line shows the annual net primary production (NPP) and the bars show the annual Palmer Drought Severity Index (PDSI).

This uncertainty exists because it can be difficult to obtain observational data of land use change over long time periods, particularly across multiple ecosystem types and large geographic areas. Recently published research by USGS scientists...
used data derived from the Landsat satellite imagery archive to estimate the extent of land changes in the conterminous U.S. (i.e., excluding Alaska and Hawaii) and to model the impact of these changes on terrestrial ecosystem carbon balance. Researchers used the Land Use and Carbon Scenario Simulator (LUCAS) modeling framework which includes a fully-coupled model of land-use and land-cover change and ecosystem carbon dynamics. The LUCAS model incorporates key uncertainties in land use change parameters and controls for the impact of climatic variability, which allowed researchers to isolate the effects of land change on ecosystem carbon dynamics.

The USGS researchers found that land use changes since the early 1970s resulted in large declines in agricultural and forested land area with a modest increase in grassland and shrubland land area in the conterminous U.S. The largest increase in any land cover class was driven by urbanization, with a gain of nearly 115,000 km² of developed land between 1973 and 2010.

The researchers used a carbon stock-flow model to estimate how the carbon stored in live biomass, dead wood, and soil changed over time and in response to land use change. Terrestrial ecosystems of the conterminous U.S. acted as a net carbon sink during most of the 37-year study period, sequestering an average of 254 Tg C yr⁻¹ (Tg C yr⁻¹ = one teragram of carbon per year = one million metric tons). There was no noticeable trend in the land carbon sink over the study period, which averaged 282 Tg C yr⁻¹ in the 1970s, 224 Tg C yr⁻¹ in the 1980s, 284 Tg C yr⁻¹ in the 1990s, and 241 Tg C yr⁻¹ in the 2000s. However, there was considerable inter-annual variability in the land carbon sink, driven by short-term climatic variations. During at least one year (1988), ecosystems were an overall net carbon source to the atmosphere (-152 Tg C yr⁻¹) which was characterized by widespread drought and massive fires in the western U.S. Although forests were the largest contributor to the U.S. land carbon sink, forest carbon sequestration declined by 35% over the study period primarily because of aging and a decline in forest area due to land use change.

By incorporating map and satellite data accuracy assessments into their model, the USGS researchers determined that land use and land cover estimates prior to 1985 had roughly two times more uncertainty than estimates from more recent years. This higher level of uncertainty in land change data during the early years of the study contributed to a ∼16% margin of error in the annual carbon sink estimate prior to 1985. Uncertainty in net biome productivity (NBP) estimates due to land use and land cover change was reduced by nearly 50% after 1985, largely due to increased spectral and spatial resolution, improved mapping capabilities, and increased data availability.

Information from this paper highlights that continued improvements in detection and attribution of the effects of land cover change on ecosystem carbon dynamics should further reduce uncertainties. This will result in improved science-based management recommendations to optimize the climate benefits provided by wildland ecosystems in the US.

The paper, “Effects of contemporary land-use and land-cover change on the carbon balance of terrestrial ecosystems in the United States”, was published in Environmental Research Letters and is available here: http://iopscience.iop.org/article/10.1088/1748-9326/aab540/meta
Giant sequoia responses to extreme drought

Each year, the iconic giant sequoias of California’s Sierra Nevada attract millions of visitors from around the globe. Travelers come to marvel at, and be inspired by, the world’s most massive trees, all the while infusing hundreds of millions of dollars into local rural economies. As regional temperatures have risen over the last several decades, the National Park Service and U.S. Forest Service managers charged with protecting the big trees have increasingly called for detailed sequoia vulnerability maps. Such maps would help target areas for treatments aimed at increasing sequoia resilience — treatments like prescribed fire or mechanical thinning to reduce non-sequoia tree density which reduce both fire hazard and local competition for sequoias. Understandably, managers want maps of where on the landscape they can get the most “bang” from their limited management dollars.

In the middle of California’s most extreme drought on historical record, giant sequoias did something in September of 2014 that had never been reported: many of the big trees showed extensive foliage dieback (Figure 1), in magnitudes that varied across the landscape. As the foliage dieback was almost certainly a stress response to drought conditions, USGS scientists stationed in Sequoia and Kings Canyon national parks immediately recognized an opportunity to allow sequoias to reveal where they were most vulnerable to future drought.

This effort would require integrating foliage dieback maps, remote sensing, and physiological measurements. The first step – mapping foliage dieback across portions of as many sequoia groves as possible – was the most urgent. California’s first winter storms would undoubtedly knock most brittle, dead sequoia foliage to the ground, thus ending mapping efforts. Recognizing this urgency, scientists developed and tested a sampling protocol, trained a field crew, and saw the crew systematically recording foliage dieback, all in under two weeks. For both speed and safety, surveys were limited to a 150 m-wide corridor along maintained trails. Before the first big storm ended these surveys, crews hiked 64 km (40 miles) of trails in eight different sequoia groves, recording foliage dieback for 4,278 large sequoias over an area spanning 847 ha (2,093 acres).

Analyses revealed foliage dieback was highest: (1) at low elevations, probably due to higher temperatures, reduced snowpack, and earlier snowmelt; (2) in areas of low adult sequoia densities, which likely reflect intrinsically more stressful sites; and (3) on steep slopes, probably reflecting reduced water availability. However, these variables were only modestly predictive of foliage dieback, suggesting that other factors could also be important. Maps of foliage dieback patterns within groves were consistent with the possibility that subsurface hydrology (invisible to us) may play a role. For example, the central portion of the Giant Forest grove of sequoias showed extremely low foliage.

Figure 1. Giant sequoia foliage dieback in September 2014, showing the death of older, proximal shoots and retention of young green distal shoots. (credit: Nathan Stephenson, USGS. Public domain)
dieback, whereas the periphery of the grove showed high
dieback (Figure 2). This pattern indicates that the grove’s
center may receive more subsurface water than its
periphery. To test this and other possibilities, ongoing
work will integrate foliage dieback data with both remote
sensing and direct physiological measurements from
sequoia crowns taken during and following the drought.

Data integration will proceed over the next few years as
part of the broader “Leaf to Landscape” collaboration
between USGS scientists, tree physiologists at the
University of California, Berkeley, and remote sensors at
the Carnegie Institute of Science. In addition to broadly
improving our understanding of giant sequoia responses
to extreme drought and warmer temperatures, this work
should yield giant sequoia vulnerability maps, helping
guide future efforts to increase sequoia resilience.

The paper, “Patterns and correlates of giant sequoia
foliage dieback during California’s 2012-2016 hotter
drought” was published in Forest Ecology and
Management and is available here: https://
www.sciencedirect.com/science/article/pii/
S0378112717313282

Figure 2. Mapped variation in the magnitude of giant sequoia foliage dieback within
the Giant Forest grove in 2014. Gray shading indicates the extent of Giant Forest;
white outlines indicate the approximate boundaries of the individual trail corridor
segments that were surveyed for foliage dieback. Note that the color scale is not
linear.