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Climate and Climate Projections

Abram, N. J., H. V. McGregor, J. E. Tierney, M. N. Evans, N. P. McKay, D. S. Kaufman, and P. k. C. the. 2016. **Early onset of industrial-era warming across the oceans and continents.** Nature 536:411-418. http://10.1038/nature19082

Abstract. The evolution of industrial-era warming across the continents and oceans provides a context for future climate change and is important for determining climate sensitivity and the processes that control regional warming. Here we use post-AD 1500 palaeoclimate records to show that sustained industrial-era warming of the tropical oceans first developed during the mid-nineteenth century and was nearly synchronous with Northern Hemisphere continental warming. The early onset of sustained, significant warming in palaeoclimate records and model simulations suggests that greenhouse forcing of industrial-era warming commenced as early as the mid-nineteenth century and included an enhanced equatorial ocean response mechanism. The development of Southern Hemisphere warming is delayed in reconstructions, but this apparent delay is not reproduced in climate simulations. Our findings imply that instrumental records are too short to comprehensively assess anthropogenic climate change and that, in some regions, about 180 years of industrial-era warming has already caused surface temperatures to emerge above pre-industrial values, even when taking natural variability into account.

Behnke, R., S. Vavrus, A. Allstadt, T. Albright, W. E. Thogmartin, and V. C. Radeloff. 2016. **Evaluation of downscaled, gridded climate data for the conterminous United States.** Ecological Applications 26:1338-1351. http://10.1002/15-1061

Abstract. Weather and climate affect many ecological processes, making spatially continuous yet fine-resolution weather data desirable for ecological research and predictions. Numerous downscaled weather data sets exist, but little attempt has been made to evaluate them systematically. Here we address this shortcoming by focusing on four major questions: (1) How accurate are downscaled, gridded climate data sets in terms of temperature and precipitation estimates? (2) Are there significant regional differences in accuracy among data sets? (3) How accurate are their mean values compared with extremes? (4) Does their accuracy depend on spatial resolution? We compared eight widely used downscaled data sets that provide gridded daily weather data for recent decades across the United States. We found considerable differences among data sets and between downscaled and weather station data. Temperature is represented more accurately than precipitation, and climate averages are more accurate than weather extremes. The data set exhibiting the best agreement with station data varies among ecoregions. Surprisingly, the accuracy of the data sets does not depend on spatial resolution. Although some inherent differences among data sets and weather station data are to be expected, our findings highlight how much different interpolation methods affect downscaled weather data, even for local comparisons with nearby weather stations located inside a grid cell. More broadly, our results highlight the need for careful consideration among different available data sets in terms of which variables they describe best, where they perform best, and their resolution, when selecting a downscaled weather data set for a given ecological application.

Blunden, J., and D. S. Arndt, eds. 2016. **State of the climate in 2015.** Bulletin of the American Meteorological Society 97:S173-S226. http://doi:10.1175/2016BAMSStateoftheClimate.1

Abstract. In 2015, the dominant greenhouse gases released into Earth's atmosphere—carbon dioxide, methane, and nitrous oxide—all continued to reach new high levels. At Mauna Loa, Hawaii, the annual CO_2 concentration increased by a record 3.1 ppm, exceeding 400 ppm for the first time on record. The 2015 global CO_2 average neared this threshold, at 399.4 ppm. Additionally, one of the strongest El Niño events since at least 1950 developed in spring 2015 and continued to evolve through the year. The phenomenon was far reaching, impacting

many regions across the globe and affecting most aspects of the climate system.

Owing to the combination of El Niño and a long-term upward trend, Earth observed record warmth for the second consecutive year, with the 2015 annual global surface temperature surpassing the previous record by more than 0.1°C and exceeding the average for the mid- to late 19th century—commonly considered representative of preindustrial conditions—by more than 1°C for the first time. Above Earth's surface, lower troposphere temperatures were near-record high.

Across land surfaces, record to near-record warmth was reported across every inhabited continent. Twelve countries, including Russia and China, reported record high annual temperatures. In June, one of the most severe heat waves since 1980 affected Karachi, Pakistan, claiming over 1000 lives. On 27 October, Vredendal, South Africa, reached 48.4°C, a new global high temperature record for this month.

In the Arctic, the 2015 land surface temperature was 1.2°C above the 1981–2010 average, tying 2007 and 2011 for the highest annual temperature and representing a 2.8°C increase since the record began in 1900. Increasing temperatures have led to decreasing Arctic sea ice extent and thickness. On 25 February 2015, the lowest maximum sea ice extent in the 37-year satellite record was observed, 7% below the 1981–2010 average. Mean sea surface temperatures across the Arctic Ocean during August in ice-free regions, representative of Arctic Ocean summer anomalies, ranged from ~0°C to 8°C above average. As a consequence of sea ice retreat and warming oceans, vast walrus herds in the Pacific Arctic are hauling out on land rather than on sea ice, raising concern about the energetics of females and young animals. Increasing temperatures in the Barents Sea are linked to a community-wide shift in fish populations: boreal communities are now farther north, and long-standing Arctic species have been almost pushed out of the area.

Above average sea surface temperatures are not confined to the Arctic. Sea surface temperature for 2015 was record high at the global scale; however, the North Atlantic southeast of Greenland remained colder than average and colder than 2014. Global annual ocean heat content and mean sea level also reached new record highs. The Greenland Ice Sheet, with the capacity to contribute ~7 m to sea level rise, experienced melting over more than 50% of its surface for the first time since the record melt of 2012.

Other aspects of the cryosphere were remarkable. Alpine glacier retreat continued, and preliminary data indicate that 2015 is the 36th consecutive year of negative annual mass balance. Across the Northern Hemisphere, late-spring snow cover extent continued its trend of decline, with June the second lowest in the 49-year satellite record. Below the surface, record high temperatures at 20-m depth were measured at all permafrost observatories on the North Slope of Alaska, increasing by up to 0.66°C decade^{-1} since 2000.

In the Antarctic, surface pressure and temperatures were lower than the 1981–2010 average for most of the year, consistent with the primarily positive southern annular mode, which saw a record high index value of +4.92 in February. Antarctic sea ice extent and area had large intra-annual variability, with a shift from record high levels in May to record low levels in August. Springtime ozone depletion resulted in one of the largest and most persistent Antarctic ozone holes observed since the 1990s.

Closer to the equator, 101 named tropical storms were observed in 2015, well above the 1981–2010 average of 82. The eastern/central Pacific had 26 named storms, the most since 1992. The western north Pacific and north and south Indian Ocean basins also saw high activity. Globally, eight tropical cyclones reached the Saffir–Simpson Category 5 intensity level.

Overlaying a general increase in the hydrologic cycle, the strong El Niño enhanced precipitation variability around the world. An above-normal rainy season led to major floods in Paraguay, Bolivia, and southern Brazil. In May, the United States recorded its all-time wettest month in its 121-year national record. Denmark and Norway reported their second and third wettest year on record, respectively, but globally soil moisture

was below average, terrestrial groundwater storage was the lowest in the 14-year record, and areas in “severe” drought rose from 8% in 2014 to 14% in 2015. Drought conditions prevailed across many Caribbean island nations, Colombia, Venezuela, and northeast Brazil for most of the year. Several South Pacific countries also experienced drought. Lack of rainfall across Ethiopia led to its worst drought in decades and affected millions of people, while prolonged drought in South Africa severely affected agricultural production. Indian summer monsoon rainfall was just 86% of average. Extremely dry conditions in Indonesia resulted in intense and widespread fires during August–November that produced abundant carbonaceous aerosols, carbon monoxide, and ozone. Overall, emissions from tropical Asian biomass burning in 2015 were almost three times the 2001–14 average.

Brewer, M. C., and C. F. Mass. 2016. **Projected changes in western U.S. large-scale summer synoptic circulations and variability in CMIP5 models.** Journal of Climate 29:5965-5978. http://doi:10.1175/JCLI-D-15-0598.1

Abstract. Large-scale synoptic circulations have a profound effect on western U.S. summer weather and climate. Heat waves, water availability, the distribution of monsoonal moisture, fire-weather conditions, and other phenomena are impacted by the position and amplitude of large-scale synoptic circulations. Furthermore, regional weather is modulated by the interactions of the large-scale flow with terrain and land–water contrasts. It is therefore crucial to understand projected changes in large-scale circulations and their variability under anthropogenic global warming.

Although recent research has examined changes in the jet stream, storm tracks, and synoptic disturbances over the Northern Hemisphere under global warming, most papers have focused on the cold season. In contrast, this work analyzes the projected trends in the spatial distribution and amplitude of large-scale synoptic disturbances over the western United States and eastern Pacific during July and August. It is shown that CMIP5 models project weaker mean midtropospheric gradients in geopotential height as well as attenuated temporal variability in geopotential height, temperature, vorticity, vertical motion, and sea level pressure over this region. Most models suggest reduced frequency of troughs and increased frequency of ridges over the western United States. These changes in the variability of synoptic disturbances have substantial implications for future regional weather and climate.

Kutta, E., and J. A. Hubbart. 2016. **Reconsidering meteorological seasons in a changing climate.** Climatic Change 137:511-524. http://10.1007/s10584-016-1704-3

Abstract. Traditional definitions of seasonality are insufficient to reflect changes associated with a swiftly changing climate. Regional changes in season onset and length using surface based metrics are well documented, but hemispheric assessments using tropospheric metrics has received little attention. The long-term average of six-hourly analyses of temperature on isobaric surfaces, provided by the Twentieth Century Reanalysis Project, is separated here into quartiles to determine climatologic seasonal end dates. Annual season end dates are defined as the date when the 5-day moving average rose above (winter and spring) or fell below (summer and fall) the long term mean. Climatic season end dates fall between meteorological and

astronomical season end dates. The length of summer has increased by an average of 13 days and the length of winter has decreased by an average of 20 days, which are more substantial seasonal changes than previous studies. These changes in season length have occurred largely within the past 36 years, corresponding to most aggressive anthropogenic climate change. Results show that the planetary boundary layer is warming at nearly twice the rate of the free troposphere. The spatial distribution of warming suggests that topographically induced weather systems are collocated with maxima or minima in free tropospheric and boundary layer temperature slope. Furthermore, regions of greatest ensemble spread are not collocated with relative maxima or minima in free troposphere or boundary layer temperature slope. This improved assessment of seasonal transitions is useful to climatologists, agricultural land managers, and scientists interested in seasonally driven biology, hydrology and biogeochemical processes.

Norris, J. R., R. J. Allen, A. T. Evan, M. D. Zelinka, C. W. O'Dell, and S. A. Klein. 2016. **Evidence for climate change in the satellite cloud record.** Nature 536:72-75. http://10.1038/nature18273

Abstract. Clouds substantially affect Earth's energy budget by reflecting solar radiation back to space and by restricting emission of thermal radiation to space. They are perhaps the largest uncertainty in our understanding of climate change, owing to disagreement among climate models and observational datasets over what cloud changes have occurred during recent decades and will occur in response to global warming. This is because observational systems originally designed for monitoring weather have lacked sufficient stability to detect cloud changes reliably over decades unless they have been corrected to remove artefacts. Here we show that several independent, empirically corrected satellite records exhibit large-scale patterns of cloud change between the 1980s and the 2000s that are similar to those produced by model simulations of climate with recent historical external radiative forcing. Observed and simulated cloud change patterns are consistent with poleward retreat of mid-latitude storm tracks, expansion of subtropical dry zones, and increasing height of the highest cloud tops at all latitudes. The primary drivers of these cloud changes appear to be increasing greenhouse gas concentrations and a recovery from volcanic radiative cooling. These results indicate that the cloud changes most consistently predicted by global climate models are currently occurring in nature.

Sévellec, F., B. Sinha, and N. Skliris. 2016. **The rogue nature of hiatuses in a global warming climate.** Geophysical Research Letters 43:8169-8177. http://10.1002/2016GL068950

Abstract. The nature of rogue events is their unlikelihood and the recent unpredicted decade-long slowdown in surface warming, the so-called hiatus, may be such an event. However, given decadal variability in climate, global surface temperatures were never expected to increase monotonically with increasing radiative forcing. Here surface air temperature from 20 climate models is analyzed to estimate the historical and future likelihood of hiatuses and "surges" (faster than expected warming), showing that the global hiatus of the early 21st century was extremely unlikely. A novel analysis of future climate scenarios suggests that hiatuses will almost vanish and surges will strongly intensify by 2100 under a "business as usual" scenario. For "CO_2 stabilisation" scenarios, hiatus, and surge characteristics revert to typical 1940s values. These results suggest to study the hiatus of the early 21st century and future reoccurrences as rogue events, at the limit of the variability of current climate modelling capability.

Carbon and Carbon Storage

Brunet-Navarro, P., H. Jochheim, and B. Muys. 2016. **Modelling carbon stocks and fluxes in the wood product sector: a comparative review.** Global Change Biology 22:2555-2569. http://10.1111/gcb.13235

Abstract. In addition to forest ecosystems, wood products are carbon pools that can be strategically managed to mitigate climate change. Wood product models (WPMs) simulating the carbon balance of wood production, use and end of life can complement forest growth models to evaluate the mitigation potential of the forest sector as a whole. WPMs can be used to compare scenarios of product use and explore mitigation strategies. A considerable number of WPMs have been developed in the last three decades, but there is no review available analysing their functionality and performance. This study analyses and compares 41 WPMs. One surprising initial result was that we discovered the erroneous implementation of a few concepts and assumptions in some of the models. We further described and compared the models using six model characteristics (*bucking allocation, industrial processes, carbon pools, product removal, recycling and substitution effects*) and three model-use characteristics

(*system boundaries, model initialization and evaluation of results*). Using a set of indicators based on the model characteristics, we classified models using a hierarchical clustering technique and differentiated them according to their increasing degrees of complexity and varying levels of user support. For purposes of simulating carbon stock in wood products, models with a simple structure may be sufficient, but to compare climate change mitigation options, complex models are needed. The number of models has increased substantially over the last ten years, introducing more diversity and accuracy. Calculation of substitution effects and recycling has also become more prominent. However, the lack of data is still an important constraint for a more realistic estimation of carbon stocks and fluxes. Therefore, if the sector wants to demonstrate the environmental quality of its products, it should make it a priority to provide reliable life cycle inventory data, particularly regarding aspects of time and location.

Clough, B. J., M. B. Russell, G. M. Domke, and C. W. Woodall. 2016. **Quantifying allometric model uncertainty for plot-level live tree biomass stocks with a data-driven, hierarchical framework.** Forest Ecology and Management 372:175-188. http://dx.doi.org/10.1016/j.foreco.2016.04.001

Abstract. Accurate uncertainty assessments of plot-level live tree biomass stocks are an important precursor to estimating uncertainty in annual national greenhouse gas inventories (NGHGIs) developed from forest inventory data. However, current approaches employed within the United States' NGHGI do not specifically incorporate methods to address error in tree-scale biomass models and as a result may misestimate overall uncertainty surrounding plot-scale assessments. We present a data-driven, hierarchical modeling approach to predict both total aboveground and foliage biomass for inventory plots within the US Forest Service Forest Inventory and Analysis (FIA) program, informed by a large multispecies felled-tree dataset. Our results reveal substantial plot-scale relative uncertainties for total aboveground biomass (11–155% of predicted means) with even larger uncertainties for foliage biomass (27–472%). In addition, we found different distributions of total aboveground and foliage biomass when compared with other generalized biomass models for North America. These results suggest a greater contribution of allometric models to the overall uncertainty of biomass stock estimates than what has been previously reported by the literature. While the relative performance of the hierarchical model is influenced by biases within the fitting data, particularly for woodland and conifer species, our results suggest that poor representation of individual tree model error may lead to

unrealistically high confidence in plot-scale estimates of biomass stocks derived from forest inventory data. However, improvements to model design and the quality of felled-tree data for fitting and validation may offer substantial improvements in the accuracy and precision of NGHGIs.

Gómez-Gener, L., B. Obrador, R. Marcé, V. Acuña, N. Catalán, J. P. Casas-Ruiz, S. Sabater, I. Muñoz, and D. von Schiller. 2016. **When water vanishes: magnitude and regulation of carbon dioxide emissions from dry temporary streams.** Ecosystems 19:710-723. http://10.1007/s10021-016-9963-4

Abstract. Most fluvial networks worldwide include watercourses that recurrently cease to flow and run dry. The spatial and temporal extent of the dry phase of these temporary watercourses is increasing as a result of global change. Yet, current estimates of carbon emissions from fluvial networks do not consider temporary watercourses when they are dry. We characterized the magnitude and variability of carbon emissions from dry watercourses by measuring the carbon dioxide (CO_2) flux from 10 dry streambeds of a fluvial network during the dry period and comparing it to the CO_2 flux from the same streambeds during the flowing period and to the CO_2 flux from their adjacent upland soils. We also looked for potential drivers regulating the CO_2 emissions by examining the main physical and chemical properties of dry streambed sediments and adjacent upland soils. The CO_2 efflux from dry streambeds (mean ± SD = 781.4 ± 390.2 mmol m^{-2} day^{-1}) doubled the CO2 efflux from flowing streambeds (305.6 ± 206.1 mmol m^{-2} day^{-1}) and was comparable to the CO_2 efflux from upland soils (896.1 ± 263.2 mmol m^{-2} day^{-1}). However, dry streambed sediments and upland soils were physicochemically distinct and differed in the variables regulating their CO_2 efflux. Overall, our results indicate that dry streambeds constitute a unique and biogeochemically active habitat that can emit significant amounts of CO_2 to the atmosphere. Thus, omitting CO_2 emissions from temporary streams when they are dry may overlook the role of a key component of the carbon balance of fluvial networks.

Liu, R., E. Cieraad, Y. Li, and J. Ma. 2016. **Precipitation pattern determines the inter-annual variation of herbaceous layer and carbon fluxes in a phreatophyte-dominated desert ecosystem.** Ecosystems 19:601-614. http://10.1007/s10021-015-9954-x

Abstract. Arid and semi-arid ecosystems dominated by shrubby species are an important component in the global carbon cycle but are largely under-represented in studies of the effect of climate change on carbon flux. This study synthesizes data from long-term eddy covariance measurements and experiments to assess how changes in ecosystem composition, driven by precipitation patterns, affect inter-annual variability of carbon flux and their components in a halophyte desert community dominated by deep-rooted shrubs (phreatophytes, which depend on groundwater as their primary water source). Our results demonstrated that the carbon balance of this community responded strongly to precipitation variations. Both pre-growing season precipitation and growing season precipitation frequency significantly affected inter-annual variations in ecosystem carbon flux. Heavy pre-growing season precipitation (November–April, mostly as snow) increased annual net ecosystem carbon exchange, by facilitating the growth and carbon assimilation of shallow-rooted annual plants, which used spring and summer precipitation to increase community productivity. Sufficient pre-growing season precipitation led to more germination and growth of shallow-rooted annual plants. When followed by high-frequency growing season precipitation, community productivity of this desert ecosystem was lifted to the level of grassland or forest ecosystems. The long-term observations and experimental results confirmed that precipitation patterns and the herbaceous component were dominant drivers of the carbon dynamics in this phreatophyte-dominated desert ecosystem. This study illustrates the importance of inter-annual variations in climate and ecosystem composition for the carbon flux in arid and semi-arid ecosystems. It also highlights the important effect of changing frequency and seasonal pattern of precipitation on the regional and global carbon cycle in the coming decades.

Mystakidis, S., E. L. Davin, N. Gruber, and S. I. Seneviratne. 2016. **Constraining future terrestrial carbon cycle projections using observation-based water and carbon flux estimates.** Global Change Biology 22:2198-2215. http://10.1111/gcb.13217

Abstract. The terrestrial biosphere is currently acting as a sink for about a third of the total anthropogenic CO_2 emissions. However, the

future fate of this sink in the coming decades is very uncertain, as current earth system models (ESMs) simulate diverging responses of the terrestrial carbon cycle to upcoming climate change. Here, we use observation-based constraints of water and carbon fluxes to reduce uncertainties in the projected terrestrial carbon cycle response derived from simulations of ESMs conducted as part of the 5th phase of the Coupled Model Intercomparison Project (CMIP5). We find in the ESMs a clear linear relationship between present-day evapotranspiration (ET) and gross primary productivity (GPP), as well as between these present-day fluxes and projected changes in GPP, thus providing an emergent constraint on projected GPP. Constraining the ESMs based on their ability to simulate present-day ET and GPP leads to a substantial decrease in the projected GPP and to a ca. 50% reduction in the associated model spread in GPP by the end of the century. Given the strong correlation between projected changes in GPP and in NBP in the ESMs, applying the constraints on net biome productivity (NBP) reduces the model spread in the projected land sink by more than 30% by 2100. Moreover, the projected decline in the land sink is at least doubled in the constrained ensembles and the probability that the terrestrial biosphere is turned into a net carbon source by the end of the century is strongly increased. This indicates that the decline in the future land carbon uptake might be stronger than previously thought, which would have important implications for the rate of increase in the atmospheric CO_2 concentration and for future climate change.

Neeti, N., and R. Kennedy. 2016. **Comparison of national level biomass maps for conterminous US: understanding pattern and causes of differences.** Carbon Balance and Management 11:1-20. http://10.1186/s13021-016-0060-y

Abstract. As Earth observation satellite data proliferate, so too do maps derived from them. Even when two co-located maps are produced with low overall error, the spatial distribution of error may not be the same. Increasingly, methods will be needed to understand differences among purportedly similar products. For this study, we have used the four aboveground biomass (AGB) maps for conterminous US generated under NASA's Carbon Monitoring System. We have developed systematic approach to (1) assess both the absolute accuracy of individual maps and assess the spatial patterns of agreement among maps, and (2) investigate potential causes of the spatial structure of agreement among maps to gain insight into reliability of methodological choices in map making.

Drought

Ge, Y., T. Apurv, and X. Cai. 2016. **Spatial and temporal patterns of drought in the Continental U.S. during the past century.** Geophysical Research Letters 43:6294-6303. http://10.1002/2016GL069660

Abstract. This study investigates the spatial and temporal patterns of multiple drought characteristics (duration, severity, and intensity) under different return periods during 1900–2012 in the Continental U.S. (CONUS). We find two significant patterns: Pattern I shows persistent droughts in western and eastern U.S. and the Great Plains, which experienced large variations in the drought characteristics over long time; Pattern II shows transient droughts in the interior of CONUS, which experienced short-term variations in drought characteristics. Trend analysis shows that duration, severity, and intensity of droughts under the various return periods are increasing in most of the Pattern I regions. Moreover, spatial distributions of duration, severity, and intensity of more frequent and less severe drought events are found to be different from those of less frequent and more severe droughts in the same time period; trends in these drought characteristics at long and short return periods are different at some locations, showing the different trends of extreme and mild droughts.

Kormos, P. R., C. H. Luce, S. J. Wenger, and W. R. Berghuijs. 2016. **Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams.** Water Resources Research 52:4990-5007. http://10.1002/2015WR018125

Abstract. Path analyses of historical streamflow data from the Pacific Northwest indicate that the precipitation amount has been the dominant control on the magnitude of low streamflow extremes compared to the air temperature-affected timing of snowmelt runoff. The relative sensitivities of low streamflow to precipitation and temperature changes have important implications for adaptation planning because global circulation models produce relatively robust estimates of air temperature changes but have large uncertainties in projected precipitation amounts in the Pacific Northwest U.S. Quantile regression analyses indicate that low streamflow extremes from the majority of catchments in this study have declined from 1948 to 2013, which may significantly affect terrestrial and aquatic ecosystems, and water resource management. Trends in the 25th percentile of mean

annual streamflow have declined and the center of timing has occurred earlier. We quantify the relative influences of total precipitation and air temperature on the annual low streamflow extremes from 42 stream gauges using mean annual streamflow as a proxy for precipitation amount effects and streamflow center of timing as a proxy for temperature effects on low flow metrics, including 7q10 summer (the minimum 7 day flow during summer with a 10 year return period), mean August, mean September, mean summer, 7q10 winter, and mean winter flow metrics. These methods have the benefit of using only readily available streamflow data, which makes our results robust against systematic errors in high elevation distributed precipitation data. Winter low flow metrics are weakly tied to both mean annual streamflow and center of timing.

Kwon, H.-H., and U. Lall. 2016. **A copula-based nonstationary frequency analysis for the 2012–2015 drought in California.** Water Resources Research 52:5662-5675. http://10.1002/2016WR018959

Abstract. Using a multicentury reconstruction of drought, we investigate how rare the 2012–2015 California drought is. A Bayesian approach to a nonstationary, bivariate probabilistic model, including the estimation of copula parameters is used to assess the time-varying return period of the current drought. Both the duration and severity of drought exhibit similar multicentury trends. The period from 800 to 1200 A.D. was perhaps more similar to the recent period than the period from 1200 to 1800 A.D. The median return period of the recent drought accounting for both duration and severity, varies from approximately 667–2652 years, if the model parameters from the different time periods are considered. However, we find that the recent California drought is of unprecedented severity, especially given the relatively modest duration of the drought. The return period of the severity of the recent drought given its 4 year duration is estimated to be nearly 21,000 years.

Margulis, S. A., G. Cortés, M. Girotto, L. S. Huning, D. Li, and M. Durand. 2016. **Characterizing the extreme 2015 snowpack deficit in the Sierra Nevada (USA) and the implications for drought recovery.** Geophysical Research Letters 43:6341-6349. http://10.1002/2016GL068520

Abstract. Analysis of the Sierra Nevada (USA) snowpack using a new spatially distributed snow reanalysis data set, in combination with

longer term in situ data, indicates that water year 2015 was a truly extreme (dry) year. The range-wide peak snow volume was characterized by a return period of over 600 years (95% confidence interval between 100 and 4400 years) having a strong elevational gradient with a return period at lower elevations over an order of magnitude larger than those at higher elevations. The 2015 conditions, occurring on top of three previous drought years, led to an accumulated (multiyear) snowpack deficit of ~ −22 km3, the highest over the 65 years analyzed. Early estimates based on 1 April snow course data indicate that the snowpack drought deficit will not be overcome in 2016, despite historically strong El Niño conditions. Results based on a probabilistic Monte Carlo simulation show that recovery from the snowpack drought will likely take about 4 years.

Extreme Events

Shields, C. A., and J. T. Kiehl. 2016. **Simulating the Pineapple Express in the half degree Community Climate System Model, CCSM4.** Geophysical Research Letters 43:7767-7773. http://10.1002/2016GL069476

Abstract. Atmospheric rivers are recognized as major contributors to the poleward transport of water vapor. Upon reaching land, these phenomena also play a critical role in extreme precipitation and flooding events. The Pineapple Express (PE) is defined as an atmospheric river extending out of the deep tropics and reaching the west coast of North America. Community Climate System Model (CCSM4) high-resolution ensemble simulations for the twentieth and 21st centuries are diagnosed to identify the PE. Analysis of the twentieth century simulations indicated that the CCSM4 accurately captures the spatial and temporal climatology of the PE. Analysis of the end 21st century simulations indicates a significant increase in storm duration and intensity of precipitation associated with landfall of the PE. Only a modest increase in the number of atmospheric rivers of a few percent is projected for the end of 21st century.

Woldemeskel, F., and A. Sharma. 2016. **Should flood regimes change in a warming climate? The role of antecedent moisture conditions.** Geophysical Research Letters 43:7556-7563. http://10.1002/2016GL069448

Abstract. Assessing changes to flooding is important for designing new and redesigning existing infrastructure to withstand future climates. While there is speculation that floods are likely to intensify in the future, this question is often difficult to assess due to inadequate records on streamflow extremes. An alternate way of determining possible extreme flooding is through assessment of the two key factors that lead to the intensification of floods: the intensification of causative rainfall and changes in the wetness conditions prior to rainfall. This study assesses global changes in the antecedent wetness prior to extreme rainfall. Our results indicate a significant increase in the antecedent moisture in Australia and Africa over the last century; however, there was also a decrease in Eurasia and insignificant change in North America. Given the nature of changes found in this study, any future flood assessment for global warming conditions should take into account antecedent moisture conditions.

Phenology Changes

Xu, C., H. Liu, A. P. Williams, Y. Yin, and X. Wu. 2016. **Trends toward an earlier peak of the growing season in Northern Hemisphere mid-latitudes.** Global Change Biology 22:2852-2860. http://10.1111/gcb.13224

Abstract. Changes in peak photosynthesis timing (PPT) could substantially change the seasonality of the terrestrial carbon cycle. Spring PPT in dry regions has been documented for some individual plant species on a stand scale, but both the spatio-temporal pattern of shifting PPT on a continental scale and its determinants remain unclear. Here, we use satellite measurements of vegetation greenness to find that the majority of Northern Hemisphere, mid-latitude vegetated area experienced a trend toward earlier PPT during 1982–2012, with significant trends of an average of 0.61 day yr^{-1} across 19.4% of areas. These shifts correspond to increased annual accumulation of growing degree days (GDD) due to warming and are most highly concentrated in the eastern United States and Europe. Earlier mean PPT is generally a trait common among areas with summer temperatures higher than 27.6 ± 2.9 °C, summer precipitation lower than 84.2 ± 41.5 mm, and fraction of cold season

precipitation greater than 89.2 ± 1.5%. The trends toward earlier PPT discovered here have co-occurred with overall increases in vegetation greenness throughout the growing season, suggesting that summer drought is not a dominant driver of these trends. These results imply that continued warming may facilitate continued shifts toward earlier PPT and cause these trends to become more pervasive, with important implications for terrestrial carbon, water, nutrient, and energy budgets.

Species Range Changes

Baker, D. J., A. J. Hartley, S. H. M. Butchart, and S. G. Willis. 2016. **Choice of baseline climate data impacts projected species' responses to climate change.** Global Change Biology 22:2392-2404. http://10.1111/gcb.13273

Abstract. Climate data created from historic climate observations are integral to most assessments of potential climate change impacts, and frequently comprise the baseline period used to infer species-climate relationships. They are often also central to downscaling coarse resolution climate simulations from General Circulation Models (GCMs) to project future climate scenarios at ecologically relevant spatial scales. Uncertainty in these baseline data can be large, particularly where weather observations are sparse and climate dynamics are complex (e.g. over mountainous or coastal regions). Yet, importantly, this uncertainty is almost universally overlooked when assessing potential responses of species to climate change. Here, we assessed the importance of historic baseline climate uncertainty for projections of species' responses to future climate change. We built species distribution models (SDMs) for 895 African bird species of conservation concern, using six different climate baselines. We projected these models to two future periods (2040–2069, 2070–2099), using downscaled climate projections, and calculated species turnover and changes in species-specific climate suitability. We found that the choice of baseline climate data constituted an important source of uncertainty in projections of both species turnover and species-specific climate suitability, often comparable with, or more important than, uncertainty arising from the choice of GCM. Importantly, the relative contribution of these factors to projection uncertainty varied spatially. Moreover, when projecting SDMs to sites of biodiversity importance (Important Bird and Biodiversity Areas), these uncertainties altered site-level impacts, which could affect conservation prioritization. Our

results highlight that projections of species' responses to climate change are sensitive to uncertainty in the baseline climatology. We recommend that this should be considered routinely in such analyses.

Cánovas, F., C. Magliozzi, F. Mestre, J. A. Palazón, and M. González-Wangüemert. 2016. **ENiRG: R-GRASS interface for efficiently characterizing the ecological niche of species and predicting habitat suitability.** Ecography 39:593-598. http://10.1111/ecog.01426

Abstract. At the base of species distribution modelling is the ecological niche concept, which describes species' response to distribution of resources. The ecological niche factor analysis, which is implemented in ENiRG, allows to reconstruct species' niche from a set of environmental variables, describing the suitability of the habitat where species occurs. ENiRG overcomes the inefficient management of large volumes of spatial information from wide study areas, high resolution or high number of environmental descriptors. This package also offers the possibility of habitat suitability classification, projection of distributions under different past or future climate scenarios and a GUI to access the functionalities.

Hooftman, D. A. P., B. Edwards, and J. M. Bullock. 2016. **Reductions in connectivity and habitat quality drive local extinctions in a plant diversity hotspot.** Ecography 39:583-592. http://10.1111/ecog.01503

Abstract. It is well documented that habitat loss is a major cause of biodiversity decline. However, the roles of the different aspects of habitat loss in local extinctions are less understood. Anthropogenic destruction of an area of habitat causes immediate local extinction but subsequently three additional gradual drivers influence the likelihood of delayed extinction: decreased habitat patch size, lower connectivity and habitat deterioration. We investigated the role of these drivers in local extinctions of 82 declining species in a UK biodiversity hotspot. We combined a unique set of ≈ 7000 vegetation surveys and habitat maps from the 1930s with contemporary species’ occurrences. We extrapolated from these surveys to the whole 2500-km^2 study area using habitat suitability surfaces. The strengths of drivers in explaining local extinctions over this 70 yr period were determined by contrasting connectivity, patch size and habitat quality loss for locations at which a species went extinct and those with persisting occurrences. Species’ occurrences declined on average by 60%, with half of local extinctions attributable to immediate habitat loss and half to the gradual processes causing delayed extinctions. On average, locations where a species persisted had a 73% higher contemporary connectivity than those suffering extinctions, but showed no differences in historical connectivity. Furthermore, locations with extinctions experienced a 37% greater decline in suitability associated with changes in habitat type. The strength of the drivers and the proportion of extinctions depended on the species' habitat specialism, but were affected only minimally by life-history characteristics. In conclusion, we identified a hierarchy of drivers influencing local extinction: with connectivity loss being the strongest, suitability change being moderately important, but changes in habitat patch size having only weak effects. We suggest conservation efforts could be most effective by strengthening connectivity along with reducing habitat deterioration, which would benefit a wide range of species.

Leroy, B., C. N. Meynard, C. Bellard, and F. Courchamp. 2016. **virtualspecies, an R package to generate virtual species distributions.** Ecography 39:599-607. http://10.1111/ecog.01388

Abstract. virtualspecies is a freely available package for R designed to generate virtual species distributions, a procedure increasingly used in ecology to improve species distribution models. This package combines the existing methodological approaches with the objective of generating virtual species distributions with increased ecological realism. The package includes 1) generating the probability of occurrence of a virtual species from a spatial set of environmental conditions (i.e. environmental suitability), with two different approaches; 2) converting the environmental suitability into presence–absence with a probabilistic approach; 3) introducing dispersal limitations in the realised virtual species distributions and 4) sampling occurrences with different biases in the sampling procedure. The package was designed to be extremely flexible, to allow users to simulate their own defined species–environment relationships, as well as to provide a fine control over every simulation parameter. The package also includes a function to generate random virtual species distributions. We provide a simple example in this paper showing how increasing ecological realism of the virtual species impacts the predictive performance of species distribution models. We expect that this new package will be valuable to researchers willing to test techniques and protocols of species distribution models as well as various biogeographical hypotheses.

Forest Vegetation

Clark, J. S., L. Iverson, C. W. Woodall, C. D. Allen, D. M. Bell, D. C. Bragg, A. W. D'Amato, F. W. Davis, M. H. Hersh, I. Ibanez, S. T. Jackson, S. Matthews, N. Pederson, M. Peters, M. W. Schwartz, K. M. Waring, and N. E. Zimmermann. 2016. **The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States.** Global Change Biology 22:2329-2352. http://10.1111/gcb.13160

Abstract. We synthesize insights from current understanding of drought impacts at stand-to-biogeographic scales, including management options, and we identify challenges to be addressed with new research. Large stand-level shifts underway in western forests already are showing the importance of interactions involving drought, insects, and fire. Diebacks, changes in composition and structure, and shifting range limits are widely observed. In the eastern US, the effects of increasing drought are becoming better understood at the level of individual trees, but this knowledge cannot yet be confidently translated to predictions of changing structure and diversity of forest stands. While eastern forests have not experienced the types of changes seen in western forests in recent decades, they too are vulnerable to drought and could experience significant changes with increased severity, frequency, or duration in drought. Throughout the continental United States, the combination of projected large climate-induced shifts in suitable habitat from modeling studies and limited potential for the rapid migration of tree populations suggests that changing tree and forest biogeography could substantially lag habitat shifts already underway. Forest management practices can partially ameliorate drought impacts through reductions in stand density, selection of drought-tolerant species and genotypes, artificial regeneration, and the development of multistructured stands. However, silvicultural treatments also could exacerbate drought impacts unless implemented with careful attention to site and stand characteristics. Gaps in our understanding should motivate new research on the effects of interactions involving climate and other species at the stand scale and how interactions and multiple responses are represented in models. This assessment indicates that, without a stronger empirical basis for drought impacts at the stand scale, more complex models may provide limited guidance.

Donato, D. C., B. J. Harvey, and M. G. Turner. 2016. **Regeneration of montane forests 24 years after the 1988 Yellowstone fires: A fire-catalyzed shift in lower treelines?** Ecosphere 7:e01410. http://10.1002/ecs2.1410

Abstract. Forests near the lower limit of montane tree cover are expected to be particularly vulnerable to warming climate, potentially converting to non-forest for prolonged periods if affected by canopy-removing disturbances. Such disturbance-catalyzed shifts are by nature stochastic, offering few opportunities to test these predictions. We capitalized on a landmark event exemplary of recent large disturbances—the 1988 wildfires in Yellowstone National Park (USA)—to investigate long-term (24-yr) regeneration dynamics in Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) forests, which compose the lower treeline yet have received little study. We tested the hypothesis that, under current conditions (warmest decades in last 6000 yr), dry lower-margin stands are less apt to attain self-replacement than adjacent, but more mesic, stands farther from the ecotone. Mesic sites characterized by dense forests prefire regenerated robustly regardless of burn severity, even in large high-severity patches, whereas dry sites did so only if nearby seed sources survived (i.e., small patch size or moderate burn severity). Regeneration continued over two decades, peaking between ~5 and 15 yr, with mesic stands continuing regenerating beyond 15 yr to a greater degree than dry stands. Self-replacement of stands by 24 yr postfire was nearly universal in mesic stands, variable but common in dry stands not adjacent to the lower ecotone, and uncommon in dry stands near the ecotone—particularly if burned at high severity. Whether the lack of regeneration in ecotonal stands is categorically directional with warming climate or part of a long-term cycle is unresolved, but we estimate that the 1988 fires converted > 4000 ha of lower-montane forest to grass/sage steppe for at least several decades, possibly indefinitely given current trends in climate. These data support the notion that climate-driven shifts in vegetation cover are likely to occur in punctuated fashion with disturbances, with relatively abrupt implications for montane forest cover, biogeography, and ecosystem function.

Kretchun, A. M., E. L. Loudermilk, R. M. Scheller, M. D. Hurteau, and S. Belmecheri. 2016. **Climate and bark beetle effects on forest productivity — linking dendroecology with forest landscape modeling.** Canadian Journal of Forest Research 46:1026-1034. http://10.1139/cjfr-2016-0103

Abstract. In forested systems throughout the world, climate influences tree growth and aboveground net primary productivity (ANPP). The effects of extreme climate events (i.e., drought) on ANPP can be compounded by biotic factors (e.g., insect outbreaks). Understanding the contribution of each of these influences on growth requires information at multiple spatial scales and is essential for understanding regional forest response to changing climate. The mixed conifer forests of the Lake Tahoe Basin, California and Nevada, provide an opportunity to analyze biotic and abiotic influences on ANPP. Our objective was to evaluate the influence of moisture stress (climatic water deficit, CWD) and bark beetles on basin-wide ANPP from 1987 to 2006, estimated through tree core increments and a landscape simulation model (LANDIS-II). Tree ring data revealed that ANPP increased throughout this period and had a nonlinear relationship to water demand. Simulation model results showed that despite increased complexity, simulations that include moderate moisture sensitivity and bark beetle outbreaks most closely approximated the field-derived ANPP~CWD relationship. Although bark beetle outbreaks and episodic drought-induced mortality events are often correlated, decoupling them within a simulation model offers insight into assessing model performance, as well as examining how each contributes to total declines in productivity.

Liénard, J., J. Harrison, and N. Strigul. 2016. **US forest response to projected climate-related stress: a *tolerance* perspective.** Global Change Biology 22:2875-2886. http://10.1111/gcb.13291

Abstract. Although it is widely recognized that climate change will require a major spatial reorganization of forests, our ability to predict exactly how and where forest characteristics and distributions will change has been rather limited. Current efforts to predict future distribution of forested ecosystems as a function of climate include species distribution models (for fine-scale predictions) and potential vegetation climate envelope models (for coarse-grained, large-scale predictions). Here, we develop and apply an intermediate approach wherein we use stand-level tolerances of environmental stressors to understand forest distributions and vulnerabilities to anticipated climate change. In contrast to other existing models, this approach

can be applied at a continental scale while maintaining a direct link to ecologically relevant, climate-related stressors. We first demonstrate that shade, drought, and waterlogging tolerances of forest stands are strongly correlated with climate and edaphic conditions in the conterminous United States. This discovery allows the development of a tolerance distribution model (TDM), a novel quantitative tool to assess landscape level impacts of climate change. We then focus on evaluating the implications of the drought TDM. Using an ensemble of 17 climate change models to drive this TDM, we estimate that 18% of US ecosystems are vulnerable to drought-related stress over the coming century. Vulnerable areas include mostly the Midwest United States and Northeast United States, as well as high-elevation areas of the Rocky Mountains. We also infer stress incurred by shifting climate should create an opening for the establishment of forest types not currently seen in the conterminous United States.

Peltier, D. M. P., M. Fell, and K. Ogle. 2016. **Legacy effects of drought in the southwestern United States: A multi-species synthesis.** Ecological Monographs 86:312-326. http://10.1002/ecm.1219

Abstract. Understanding impacts of drought on tree growth and forest health is of major concern given projected climate change. Droughts may become more common in the Southwest due to extreme temperatures that will drive increased evapotranspiration and lower soil moisture, in combination with uncertain precipitation changes. Utilizing ~1.3 million tree-ring widths from the International Tree Ring Data Bank representing 10 species (eight conifers, two oaks) in the Southwest, we evaluated the effects of drought on tree growth. We categorized ring widths by formation year in relation to drought (pre-drought, drought year, and post-drought), and we used a mixed-effects model to estimate the effects of current and antecedent precipitation and temperature on tree growth during the post-drought recovery period. This allowed us to assess changes in sensitivity of tree growth to precipitation and temperature at multiple timescales following multiple droughts, and to evaluate drought resistance and recovery in these species. The effects of precipitation and temperature on ring widths following drought varied among species and time since drought. Across species, 16% of the climate effects (i.e., “sensitivities”) were significantly different from their pre-drought values. Species differed, with some showing increased sensitivities to precipitation and temperature following drought, and others showing decreased sensitivities. Furthermore, some species (e.g., *Abies concolor* and *Pinus ponderosa*) showed low resistance and slow

recovery, with changes in growth sensitivities persisting up to 5 yr; others (e.g., Juniper spp.) showed high resistance, such that their climatic sensitivities did not change. Among species, the importance of different antecedent climate variables changed with time since drought. Though a majority of species responded positively to same-year precipitation pre-drought, all 10 species were positively affected by same-year precipitation the second year after drought. Our results demonstrate tree growth sensitivities vary among species and with time since drought, raising questions about physiological mechanisms and implications for forest health under future drought.

Reilly, M. J., and T. A. Spies. 2016. **Disturbance, tree mortality, and implications for contemporary regional forest change in the Pacific Northwest.** Forest Ecology and Management 374:102-110. http://dx.doi.org/10.1016/j.foreco.2016.05.002

Abstract. Tree mortality is an important demographic process and primary driver of forest dynamics, yet there are relatively few plot-based studies that explicitly quantify mortality and compare the relative contribution of endogenous and exogenous disturbances at regional scales. We used repeated observations on 289,390 trees in 3673 1 ha plots on U.S. Forest Service lands in Oregon and Washington to compare distributions of mortality rates among natural disturbances and vegetation zones from the mid-1990s to mid-2000s, a period characterized by drought, insect outbreaks, and large wildfires. Endogenous disturbances (e.g. pathogens, insects) were pervasive but operated at relatively low levels of mortality (<2.5%/yr) that rarely exceeded 5%/yr. Exogenous disturbances (e.g. fire, wind, landslides, avalanches) were less common and operated mostly at intermediate levels of mortality (5–25%/yr) indicative of partial-stand-replacement events. Stand-replacing mortality rates (⩾25%/yr) comprised a third of all exogenous disturbance events, occurring almost exclusively in fires. Fires were rare in wet vegetation zones and most rates were <2.5%/yr and associated with endogenous processes. Mortality rates in dry vegetation zones revealed a different set of dynamics including a more variable role of background mortality and greater proportions of mortality associated with fire and insects at partial- and stand-replacing levels. Mortality rates in early and middle stages of stand development were low compared to published rates, but rates >1%/yr in over half of the plots in late and old-growth stages corroborate previous findings of elevated mortality during the same period and indicate the potential for pervasive structural change across all vegetation zones. Partial- and stand-replacing fire were associated with most mortality, but affected a relatively small

proportion of dry vegetation zones (3.1–7.1% and 2.1–5.1%, respectively). These disturbances have likely affected regional biodiversity through the creation of early seral habitat, increased within-stand heterogeneity, and restored some aspects of historical fire regimes, but there is a need to better understand corresponding structural and compositional changes. We demonstrate the variability in the drivers, magnitude, and extent of mortality across a biophysically diverse region and highlight the need to incorporate and characterize the effects of mortality at intermediate levels to develop a more comprehensive understanding of regional forest dynamics.

Restaino, C. M., D. L. Peterson, and J. Littell. 2016. **Increased water deficit decreases Douglas fir growth throughout western US forests.** Proceedings of the National Academy of Sciences 113:9557-9562. http://10.1073/pnas.1602384113

Abstract. Changes in tree growth rates can affect tree mortality and forest feedbacks to the global carbon cycle. As air temperature increases, evaporative demand also increases, increasing effective drought in forest ecosystems. Using a spatially comprehensive network of Douglas fir (*Pseudotsuga menziesii*) chronologies from 122 locations that represent distinct climate environments in the western United States, we show that increased temperature decreases growth via vapor pressure deficit (VPD) across all latitudes. Using an ensemble of global circulation models, we project an increase in both the mean VPD associated with the lowest growth extremes and the probability of exceeding these VPD values. As temperature continues to increase in future decades, we can expect deficit-related stress to increase and consequently Douglas fir growth to decrease throughout its US range.

Schlesinger, W. H., M. C. Dietze, R. B. Jackson, R. P. Phillips, C. C. Rhoades, L. E. Rustad, and J. M. Vose. 2016. **Forest biogeochemistry in response to drought.** Global Change Biology 22:2318-2328. http://10.1111/gcb.13105

Abstract. Trees alter their use and allocation of nutrients in response to drought, and changes in soil nutrient cycling and trace gas flux (N_2O and CH_4) are observed when experimental drought is imposed on forests. In extreme droughts, trees are increasingly susceptible to attack by pests and pathogens, which can lead to major changes in nutrient flux to the soil. Extreme droughts often lead to more common and more intense forest fires, causing dramatic changes in the nutrient storage and loss from forest ecosystems. Changes in the future

manifestation of drought will affect carbon uptake and storage in forests, leading to feedbacks to the Earth's climate system. We must improve the recognition of drought in nature, our ability to manage our forests in the face of drought, and the parameterization of drought in earth system models for improved predictions of carbon uptake and storage in the world's forests.

Rangeland Vegetation

Bansal, S., and R. L. Sheley. 2016. **Annual grass invasion in sagebrush steppe: the relative importance of climate, soil properties and biotic interactions.** Oecologia 181:543-557. http://10.1007/s00442-016-3583-8

Abstract. The invasion by winter-annual grasses (AGs) such as Bromus tectorum into sagebrush steppe throughout the western USA is a classic example of a biological invasion with multiple, interacting climate, soil and biotic factors driving the invasion, although few studies have examined all components together. Across a 6000-km2 area of the northern Great Basin, we conducted a field assessment of 100 climate, soil, and biotic (functional group abundances, diversity) factors at each of 90 sites that spanned an invasion gradient ranging from 0 to 100 % AG cover. We first determined which biotic and abiotic factors had the strongest correlative relationships with AGs and each resident functional group. We then used regression and structural equation modeling to explore how multiple ecological factors interact to influence AG abundance. Among biotic interactions, we observed negative relationships between AGs and biodiversity, perennial grass cover, resident species richness, biological soil crust cover and shrub density, whereas perennial and annual forb cover, tree cover and soil microbial biomass had no direct linkage to AG. Among abiotic factors, AG cover was strongly related to climate (increasing cover with increasing temperature and aridity), but had weak relationships with soil factors. Our structural equation model showed negative effects of perennial grasses and biodiversity on AG cover while integrating the negative effects of warmer climate and positive influence of belowground processes on resident functional groups. Our findings illustrate the relative importance of biotic interactions and climate on invasive abundance, while soil properties appear to have stronger relationships with resident biota than with invasives.

Boyte, S. P., B. K. Wylie, and D. J. Major. 2016. **Cheatgrass percent cover change: comparing recent estimates to climate change — driven predictions in the northern Great Basin.** Rangeland Ecology & Management 69:265-279. http://10.1016/j.rama.2016.03.002

Abstract. Cheatgrass (*Bromus tectorum* L.) is a highly invasive species in the Northern Great Basin that helps decrease fire return intervals. Fire fragments the shrub steppe and reduces its capacity to provide forage for livestock and wildlife and habitat critical to sagebrush obligates. Of particular interest is the greater sage grouse (*Centrocercus urophasianus*), an obligate whose populations have declined so severely due, in part, to increases in cheatgrass and fires that it was considered for inclusion as an endangered species. Remote sensing technologies and satellite archives help scientists monitor terrestrial vegetation globally, including cheatgrass in the Northern Great Basin. Along with geospatial analysis and advanced spatial modeling, these data and technologies can identify areas susceptible to increased cheatgrass cover and compare these with greater sage grouse priority areas for conservation (PAC). Future climate models forecast a warmer and wetter climate for the Northern Great Basin, which likely will force changing cheatgrass dynamics. Therefore, we examine potential climate-caused changes to cheatgrass. Our results indicate that future cheatgrass percent cover will remain stable over more than 80% of the study area when compared with recent estimates, and higher overall cheatgrass cover will occur with slightly more spatial variability. The land area projected to increase or decrease in cheatgrass cover equals 18% and 1%, respectively, making an increase in fire disturbances in greater sage grouse habitat likely. Relative susceptibility measures, created by integrating cheatgrass percent cover and temporal standard deviation datasets, show that potential increases in future cheatgrass cover match future projections. This discovery indicates that some greater sage grouse PACs for conservation could be at heightened risk of fire disturbance. Multiple factors will affect future cheatgrass cover including changes in precipitation timing and totals and increases in freeze-thaw cycles. Understanding these effects can help direct land management, guide scientific research, and influence policy.

Carroll, J. M., C. A. Davis, S. D. Fuhlendorf, and R. D. Elmore. 2016. **Landscape pattern is critical for the moderation of thermal extremes.** Ecosphere 7:e01403. http://10.1002/ecs2.1403

Abstract. Temperature is highly variable across space and time at multiple scales, shapes landscape pattern, and dictates ecological processes. While our knowledge of ecological phenomena is vast relative to many landscape metrics, thermal patterns which shape landscape mosaics are largely unknown. To address this disconnect, we investigated the thermal landscape by measuring black bulb temperature (T_{bb}) at intervals as small as 15 min across 3 yr in a mixed-grass shrub vegetation community. We found that the thermal landscape was highly heterogeneous displaying a prevalence for thermal extremes (i.e., T_{bb} > 50°C) and that T_{bb} was driven by the synergism of environmental, terrain, and vegetation factors. Specifically, variation of T_{bb} on the landscape was best predicted by the inclusion of ambient temperature (T_{air}), solar radiation (S_{rad}), low woody cover, and tall woody cover as variables. Moreover, models of single vegetation parameters (i.e., bare ground, low woody, or tall woody cover) each had greater relative importance than those containing a single terrain variable (i.e., slope or aspect) based on AIC, providing evidence that vegetation is a key driver of T_{bb} on the landscape. Within the thermally heterogeneous landscape, tall woody cover moderated T_{bb} by 10°C more than bare ground, herbaceous, or low woody cover during peak diurnal heating (14:00), and was the only cover type that remained <50°C on average. Given that tall woody cover comprises only about 7% of the landscape in our study, these findings have direct conservation implications for species inhabiting shrub communities, specifically that the distribution of tall woody cover is a spatially limited but key predictor of potential thermal refugia on the landscape. Our findings also demonstrate that local interactions between vegetation and temperature can create thermal patterns that shape dynamic landscape mosaics across space and time. Furthermore, we show that structural heterogeneity can maximize thermal complexity across landscapes which can provide greater potential thermal options for organisms. However, our modeled climate projections suggest that far greater thermal extremes will be possible across increasingly larger swaths of the landscape in the future, making assessments and quantifications of thermal landscapes increasingly critical.

Copeland, S. M., S. P. Harrison, A. M. Latimer, E. I. Damschen, A. M. Eskelinen, B. Fernandez-Going, M. J. Spasojevic, B. L. Anacker, and J. H. Thorne. 2016. **Ecological effects of extreme drought on Californian herbaceous plant communities.** Ecological Monographs 86:295-311. http://10.1002/ecm.1218

Abstract. Understanding the consequences of extreme climatic events is a growing challenge in ecology. Climatic extremes may differentially affect varying elements of biodiversity, and may not always produce ecological effects exceeding those of “normal” climatic variation in space and time. We asked how the extreme drought years of 2013–2014 affected the cover, species richness, functional trait means, functional diversity, and phylogenetic diversity of herbaceous plant communities across the California Floristic Province. We compared the directions and magnitudes of these drought effects with expectations from four “pre-drought” studies of variation in water availability: (1) a watering experiment, (2) a long-term (15-yr) monitoring of interannual variability, (3) a resampling of historic (57-yr-old) plots within a warming and drying region, and (4) natural variation in communities over a broad geographic gradient in precipitation. We found that the drought was associated with consistent reductions in species richness and cover, especially for annual forbs and exotic annual grasses, but not with changes in functional or phylogenetic diversity. Except for total cover and cover of exotic annual grasses, most drought effects did not exceed quantitative expectations based on the four pre-drought studies. Qualitatively, plant community responses to the drought were most concordant with responses to pre-drought interannual rainfall variability in the 15-yr monitoring study, and least concordant with responses to the geographic gradient in precipitation. Our results suggest that, at least in the short term, extreme drought may cause only a subset of community metrics to respond in ways that exceed normal background variability.

Hamerlynck, E. P., R. L. Sheley, K. W. Davies, and T. J. Svejcar. 2016. **Postdefoliation ecosystem carbon and water flux and canopy growth dynamics in sagebrush steppe bunchgrasses.** Ecosphere 7:e01376. http://10.1002/ecs2.1376

Abstract. Developing land-use practices that lead to sustainable net primary productivity in rangelands are important, but understanding their consequences to population and community processes is not often accounted for in basic ecosystem studies. Grazed and ungrazed upland ecosystems generally do not differ in net ecosystem CO_2 exchange (NEE), but the underlying mechanisms and the concurrent

effects of defoliation to vegetative and reproductive biomass allocation are unclear. To address this, we measured evapotranspiration (ET), NEE, and its constituent fluxes of ecosystem respiration (R_{eco}) and gross ecosystem photosynthesis (GEP) with live canopy leaf area index (LAI_{live}; m2 live leaf area/m2 ground area) and aboveground leaf, culm, and reproductive biomass in plots of clipped and unclipped squirreltail (*Elymus elymoides*) and bluebunch wheatgrass (*Pseudoroegneria spicata*) growing in intact sagebrush steppe. Clipping reduced LAI_{live} by 75%, but subsequent re-growth rates in clipped plots was similar to LAI_{live} accumulation in unclipped plots. Concurrently, ET and NEE was similar between clipped and unclipped plots, with NEE primarily determined by GEP. GEP was initially lower in clipped plots, but then converged with unclipped GEP even as LAI_{live} continued to increase in both treatments. GEP convergence was driven by higher whole-plant photosynthesis (GEP_{live} = GEP/LAI_{live}) in clipped plots. Ecosystem water use efficiency (GEP/ET) was reduced by 16% with clipping, due to low GEP/ET 2 weeks following defoliation, but GEP/ET converged before GEP levels did. Proportional reproductive biomass was higher in *E. elymoides* (21.4% total biomass) than in *P. spicata* (0.5% total biomass) due to lower allocation to specific leaf and culm mass. Clipping reduced reproductive effort in *E. elymoides*, in terms of total reproductive biomass (−56%), seed mass per unit leaf area (−64%), and seed mass per flowering head (−77%). We concluded defoliation increased canopy-level light penetration, facilitating rapid recovery of ecosystem fluxes, but that allocation to vegetative regrowth supporting this led to lower reproductive effort in these range grasses. Insights from studies such as this will be useful in formulating systems-based land management strategies aimed at maintaining annual productivity and long-term population and community goals in semiarid rangeland ecosystems.

Hufkens, K., T. F. Keenan, L. B. Flanagan, R. L. Scott, C. J. Bernacchi, E. Joo, N. A. Brunsell, J. Verfaillie, and A. D. Richardson. 2016. **Productivity of North American grasslands is increased under future climate scenarios despite rising aridity.** Nature Climate Change 6:710-714. http://10.1038/nclimate2942

Abstract. Grassland productivity is regulated by both temperature and the amount and timing of precipitation. Future climate change is therefore expected to influence grassland phenology and growth, with consequences for ecosystems and economies. However, the interacting effects of major shifts in temperature and precipitation on grasslands remain poorly understood and existing modelling approaches, although typically complex, do not extrapolate or generalize well and tend to disagree under future scenarios. Here we explore the potential responses of North American grasslands to climate change using a new, data-informed vegetation–hydrological model, a network of high-frequency ground observations across a wide range of grassland ecosystems and CMIP5 climate projections. Our results suggest widespread and consistent increases in vegetation fractional cover for the current range of grassland ecosystems throughout most of North America, despite the increase in aridity projected across most of our study area. Our analysis indicates a likely future shift of vegetation growth towards both earlier spring emergence and delayed autumn senescence, which would compensate for drought-induced reductions in summer fractional cover and productivity. However, because our model does not include the effects of rising atmospheric CO_2 on photosynthesis and water use efficiency, climate change impacts on grassland productivity may be even larger than our results suggest. Increases in the productivity of North American grasslands over this coming century have implications for agriculture, carbon cycling and vegetation feedbacks to the atmosphere.

Nafus, A. M., T. J. Svejcar, and K. W. Davies. 2016. **Disturbance history, management, and seeding year precipitation influences vegetation characteristics of crested wheatgrass stands.** Rangeland Ecology & Management 69:248-256. http://10.1016/j.rama.2016.03.003

Abstract. Crested wheatgrass (*Agropyron cristatum* [L] Gaertm. and *Agropyron desertorum* [Fisch.] Schult.) has been seeded across millions of hectares of the sagebrush steppe and is often associated with native species displacement and low biological diversity. However, native vegetation composition of these seedings can be variable. To gain better understanding of the correlation between vegetation characteristics of crested wheatgrass seedings and their seeding history and management, we evaluated 121 crested wheatgrass seedings across a 54 230-km^2 area in southeastern Oregon. Higher precipitation in the year following seeding of crested wheatgrass has long-term, negative effects on Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle & Young) cover and density. Wyoming big sagebrush cover and density were positively correlated with age of seeding and time since fire. We also found that preseeding disturbance (burned, scarified, plowed, or herbicide) appears to have legacy effects on plant community characteristics. For example, herbicide-treated sites had significantly fewer shrubs than sites that were burned or scarified preseeding. Native vegetation cover and density were greater in grazed compared with ungrazed crested

wheatgrass stands. The results of this study suggest a number of factors influence native vegetation cover and density within stands of seeded crested wheatgrass. Though disturbance history and precipitation following seeding can't be modified, management actions may affect the cover and abundance of native vegetation in crested wheatgrass stands. Notably, grazing may reduce monoculture characteristics of crested wheatgrass stands and fire exclusion may promote sagebrush and perennial forbs.

Thoma, D. P., S. M. Munson, K. M. Irvine, D. L. Witwicki, and E. L. Bunting. 2016. **Semi-arid vegetation response to antecedent climate and water balance windows.** Applied Vegetation Science 19:413-429. http://10.1111/avsc.12232

Abstract. Questions. Can we improve understanding of vegetation response to water availability on monthly time scales in semi-arid environments using remote sensing methods? What climatic or water balance variables and antecedent windows of time associated with these variables best relate to the condition of vegetation? Can we develop credible near-term forecasts from climate data that can be used to prepare for future climate change effects on vegetation?

Location. Semi-arid grasslands in Capitol Reef National Park, Utah, USA.

Methods. We built vegetation response models by relating the normalized difference vegetation index (NDVI) from MODIS imagery in Mar–Nov 2000–2013 to antecedent climate and water balance variables preceding the monthly NDVI observations. We compared how climate and water balance variables explained vegetation greenness and then used a multi-model ensemble of climate and water balance models to forecast monthly NDVI for three holdout years.

Results. Water balance variables explained vegetation greenness to a greater degree than climate variables for most growing season months. Seasonally important variables included measures of antecedent water input and storage in spring, switching to indicators of drought, input or use in summer, followed by antecedent moisture availability in autumn. In spite of similar climates, there was evidence the grazed grassland showed a response to drying conditions 1 mo sooner than the ungrazed grassland. Lead times were generally short early in the growing season and antecedent window durations increased from 3 mo early in the growing season to 1 yr or more as the growing season progressed. Forecast accuracy for three holdout

years using a multi-model ensemble of climate and water balance variables outperformed forecasts made with a naïve NDVI climatology.

Conclusions. We determined the influence of climate and water balance on vegetation at a fine temporal scale, which presents an opportunity to forecast vegetation response with short lead times. This understanding was obtained through high-frequency vegetation monitoring using remote sensing, which reduces the costs and time necessary for field measurements and can lead to more rapid detection of vegetation changes that could help managers take appropriate actions.

Wheeler, M. M., M. M. Dipman, T. A. Adams, A. V. Ruina, C. R. Robins, and W. M. Meyer Iii. 2016. **Carbon and nitrogen storage in California sage scrub and non-native grassland habitats.** Journal of Arid Environments 129:119-125. http://dx.doi.org/10.1016/j.jaridenv.2016.02.013

Abstract. Human activity has altered global carbon and nitrogen cycles, leading to changes in global temperatures and plant communities. Because atmospheric carbon (C) and nitrogen (N) concentrations are affected by storage in terrestrial vegetation and soil, it is critical to understand how conversions from native to non-native vegetation may alter the C and N storage potential of terrestrial landscapes. In this study, we compared C and N storage in native California sage scrub, non-native grassland, and recovering California sage scrub habitats in the spring and fall by determining the C and N content in aboveground biomass, litter, and surface soil. Significantly more C and N were stored in intact and recovering California sage scrub than in grassland habitats. Intact and recovering sage scrub did not differ significantly in C or N storage. Our results highlight that preserving and restoring California sage scrub habitat not only provides habitat for native biodiversity, but also increases carbon and nitrogen storage potential even without restoration to intact sage scrub.

Riparian Vegetation

Warren, D. R., W. S. Keeton, P. M. Kiffney, M. J. Kaylor, H. A. Bechtold, and J. Magee. 2016. **Changing forests—changing streams: riparian forest stand development and ecosystem function in temperate headwaters.** Ecosphere 7:e01435. http://10.1002/ecs2.1435

Abstract. Light availability influences temperature, primary production, nutrient dynamics, and secondary production in aquatic ecosystems. In forested freshwater ecosystems, shading by streamside (riparian) vegetation is a dominant control on light flux and represents an important interaction at the aquatic–terrestrial interface. Changes in forest structure over time, particularly tree mortality processes that gradually increase light penetration through maturing forest canopies, are likely to influence stream light fluxes and associated ecosystem functions. We provide a set of conceptual models describing how stream light dynamics change with the development of complex canopy structure and how changes in light availability are likely to affect stream ecosystem processes. Shortly after a stand-replacing event, light flux to the stream is high, but light fluxes decline as canopies reestablish and close. Tree density, the degree of understory growth, patterns of tree mortality, and small-scale disturbances interact as drivers of multiple pathways of forest structural development. Changes in canopy structure will, in turn, influence stream light, which is expected to impact primary production and stream nutrient dynamics as well as the amount of autochthonous carbon supporting aquatic food webs. Ultimately, these conceptual models stress the importance of recovery from historic forest disturbances as well as future forest change as important factors influencing the long-term trajectories of ecosystem processes in headwaters.

Fish and Wildlife

DeBano, S. J., D. E. Wooster, J. R. Walker, L. E. McMullen, and D. A. Horneck. 2016. **Interactive influences of climate change and agriculture on aquatic habitat in a Pacific Northwestern watershed.** Ecosphere 7:e01357. http://10.1002/ecs2.1357

Abstract. Climate change and agricultural intensification are two potential stressors that may pose significant threats to aquatic habitats

in the inland Pacific Northwest over the next century. Climate change may impact running water through numerous pathways, including effects on water temperature and stream flow. In certain regions of the Pacific Northwest, agricultural activities, such as crop production, may become more profitable if water projects result in more irrigation water. If so, riparian buffers in these areas may be converted into cropland, which may in turn affect aquatic habitats through increases in sediment and agrochemical runoff into streams. We used currently available downscaled temperature and hydrology data in combination with a habitat quality framework developed for Pacific salmon and trout (*Oncorhynchus* spp.) to predict how different levels of each stressor, alone and in combination, may impact aquatic habitats in an inland Pacific Northwest watershed dominated by high-value agriculture—the Umatilla Subbasin. We developed spatially explicit predictions for how changes in stream flow and water temperature associated with three climate change scenarios and loss of riparian buffers in two agricultural intensification scenarios may impact aquatic habitats. We also examined the cumulative effects of the interaction of extreme climate change and agricultural intensification scenarios. Our results show that all three climate change scenarios are expected to primarily impact aquatic habitat in the upper Subbasin. In contrast, agricultural intensification scenarios did not have large impacts on temperature, but are predicted to affect other water quality variables in the lower Subbasin. A moderate scenario of agricultural intensification had relatively little effect on aquatic habitat, whereas the removal of all riparian buffers in agriculturally viable areas had a substantially negative effect on sediment, embeddedness, and large woody debris in the lower Subbasin. Interactions between the most extreme climate change and agricultural intensification scenarios reflected a complementarity of effects, with climate change primarily affecting the upper Subbasin and agricultural intensification primarily impacting the lower Subbasin. This work suggests that the Umatilla Subbasin and similar watersheds will present a challenging habitat for warm water- and pollution-intolerant species in the coming century.

Fischer, D. T., C. J. Still, C. M. Ebert, S. A. Baguskas, and A. Park Williams. 2016. **Fog drip maintains dry season ecological function in a California coastal pine forest.** Ecosphere 7:e01364. http://10.1002/ecs2.1364

Abstract. Fog drip is recognized as an important source of water for many ecosystems that often harbor a disproportionate fraction of endemic species. Characterizing and quantifying the ecological importance of fog drip in these ecosystems requires a range of

approaches. We report on a multi-faceted study of Bishop pine (*Pinus muricata* D. Don) along a coastal-inland transect on an island off Southern California. Hourly sampling included micrometeorology, sap flux, and soil moisture. Monthly measurements included changes in tree girth, plant water stress, and isotopic values of fogwater, rainwater, and xylem water. These data show that summertime fog drip clearly affected soil moisture and maintained aspects of tree function, including leaf water relations, sap flux dynamics, and growth rates. Although water from fog drip to the soil surface was occasionally taken up by pine trees, as quantified with isotopic measurements and a Bayesian mixing model, this utilization of fog drip was highly variable in space and time. The proportion of fogwater inferred to have been used is also much less than has been demonstrated in more mesic coastal forest ecosystems using isotopic methods. These results thus suggest high ecosystem sensitivity to even moderate amounts of fog drip, a finding with important implications as climate change differentially affects fog and rain patterns.

Hjältén, J., C. Nilsson, D. Jørgensen, and D. Bell. 2016. **Forest–stream links, anthropogenic stressors, and climate change: implications for restoration planning.** BioScience 66:646-654. http://10.1093/biosci/biw072

Abstract. The global extraction of forest and water resources has led to habitat degradation, biodiversity loss, and declines in ecosystem services. As a consequence, ecological restoration has become a global priority. Restoration efforts to offset this trend, however, are not always effective. One reason is that many restoration projects target single ecosystems and fail to acknowledge functional links between ecosystems. We synthesized current knowledge on links between forest and stream ecosystems, the effect of anthropogenic stressors on these links, and their implications for restoration planning. Many examples show that lateral subsidies, such as invertebrate prey and nutrients, are important in both terrestrial and aquatic environments. Stressors such as commercial forestry, flow regulation, stream channelization, and climate change affect these links and should be considered in restoration planning. Restoration practitioners are encouraged to view adjacent forest and stream ecosystems as one entity.

Jones, G. M., R. J. Gutiérrez, D. J. Tempel, S. A. Whitmore, W. J. Berigan, and M. Z. Peery. 2016. **Megafires: an emerging threat to old-forest species.** Frontiers in Ecology and the Environment 14:300-306. http://10.1002/fee.1298

Abstract. Increasingly frequent “megafires” in North America's dry forests have prompted proposals to restore historical fire regimes and ecosystem resilience. Restoration efforts that reduce tree densities (eg via logging) could have collateral impacts on declining old-forest species, but whether these risks outweigh the potential effects of large, severe fires remains uncertain. We demonstrate the effects of a 2014 California megafire on an iconic old-forest species, the spotted owl (*Strix occidentalis*). The probability of owl site extirpation was seven times higher after the fire (0.88) than before the fire (0.12) at severely burned sites, contributing to the greatest annual population decline observed during our 23-year study. The fire also rendered large areas of forest unsuitable for owl foraging one year post-fire. Our study suggests that megafires pose a threat to old-forest species, and we conclude that restoring historical fire regimes could benefit both old-forest species and the dry forest ecosystems they inhabit in this era of climate change.

Invertebrates

Sidder, A. M., S. Kumar, M. Laituri, and J. S. Sibold. 2016. **Using spatiotemporal correlative niche models for evaluating the effects of climate change on mountain pine beetle.** Ecosphere 7:e01396. http://10.1002/ecs2.1396

Abstract. Over the last decade, western North America has experienced the largest mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak in recorded history, and Rocky Mountain forests have been severely impacted. Although bark beetles are indigenous to North American forests, climate change has facilitated the beetle's expansion into previously unsuitable habitats. We used three correlative niche models (maximum entropy [MaxEnt], boosted regression trees, and generalized linear models) to estimate (1) the current potential distribution of the beetle in the U.S. Rocky Mountain region, (2) how this distribution has changed since historical outbreaks in the 1960s and 1970s, and (3) how the distribution may be expected to change under future climate scenarios. Additionally, we evaluated the temporal transferability of the niche models by forecasting historical models and testing the model predictions using

temporally independent outbreak data from the current outbreak. Our results indicated that there has been a significant expansion of climatically suitable habitat over the past 50 yr and that much of this expansion corresponds with an upward shift in elevation across the study area. Furthermore, our models indicated that drought was a more prominent driver of current outbreak than temperature, which suggests a change in the climatic signature between historical and current outbreaks. Projections under future conditions suggest that there will be a large reduction in climatically suitable habitat for the beetle and that high-elevation forests will continue to become more susceptible to outbreak. While all three models generated reasonable predictions, the generalized linear model correctly predicted a higher percentage of current outbreak localities when trained on historical data. Our findings suggest that researchers aiming to reduce omission error in estimates of future species responses may have greater predictive success with simpler, generalized models.

Soils and Hydrology

Barnhart, T. B., N. P. Molotch, B. Livneh, A. A. Harpold, J. F. Knowles, and D. Schneider. 2016. **Snowmelt rate dictates streamflow.** Geophysical Research Letters 43:8006-8016. http://10.1002/2016GL069690

Abstract. Declining mountain snowpack and earlier snowmelt across the western United States has implications for downstream communities. We present a possible mechanism linking snowmelt rate and streamflow generation using a gridded implementation of the Budyko framework. We computed an ensemble of Budyko streamflow anomalies (BSAs) using Variable Infiltration Capacity model-simulated evapotranspiration, potential evapotranspiration, and estimated precipitation at 1/16° resolution from 1950 to 2013. BSA was correlated with simulated baseflow efficiency (r^2 = 0.64) and simulated snowmelt rate (r^2 = 0.42). The strong correlation between snowmelt rate and baseflow efficiency (r^2 = 0.73) links these relationships and supports a possible streamflow generation mechanism wherein greater snowmelt rates increase subsurface flow. Rapid snowmelt may thus bring the soil to field capacity, facilitating below-root zone percolation, streamflow, and a positive BSA. Previous works have shown that future increases in regional air temperature may lead to earlier, slower snowmelt and hence decreased streamflow production via the mechanism proposed by this work.

Bennett, G. L., J. J. Roering, B. H. Mackey, A. L. Handwerger, D. A. Schmidt, and B. P. Guillod. 2016. **Historic drought puts the brakes on earthflows in Northern California.** Geophysical Research Letters 43:5725-5731. http://10.1002/2016GL068378

Abstract. California's ongoing, unprecedented drought is having profound impacts on the state's resources. Here we assess its impact on 98 deep-seated, slow-moving landslides in Northern California. We used aerial photograph analysis, satellite interferometry, and satellite pixel tracking to measure earthflow velocities spanning 1944–2015 and compared these trends with the Palmer Drought Severity Index, a proxy for soil moisture and pore pressure that governs landslide motion. We find that earthflow velocities reached a historical low in the 2012–2015 drought, but that their deceleration began at the turn of the century in response to a longer-term moisture deficit. Our analysis implies depth-dependent sensitivity of earthflows to climate forcing, with thicker earthflows reflecting longer-term climate trends and thinner earthflows exhibiting less systematic velocity variations. These findings have implications for mechanical-hydrologic interactions that link landslide movement with climate change as well as sediment delivery in the region.

Najafi, M. R., F. W. Zwiers, and N. P. Gillett. 2016. **Attribution of the spring snow cover extent decline in the Northern Hemisphere, Eurasia and North America to anthropogenic influence.** Climatic Change 136:571-586. http://10.1007/s10584-016-1632-2

Abstract. While it is generally accepted that the observed reduction of the Northern Hemisphere spring snow cover extent (SCE) is linked to warming of the climate system caused by human induced greenhouse gas emissions, it has been difficult to robustly quantify the anthropogenic contribution to the observed change. This study addresses the challenge by undertaking a formal detection and attribution analysis of SCE changes based on several observational datasets with different structural characteristics, in order to account for the substantial observational uncertainty. The datasets considered include a blended in situ-satellite dataset extending from 1923 to 2012 (Brown), the National Oceanic and Atmospheric Administration (NOAA) snow chart Climate Data Record for 1968–2012, the Global Land Data Assimilation System version 2.0 (GLDAS-2 Noah) reanalysis for 1951–2010, and the NOAA 20th-century reanalysis, version 2 (20CR2) covering 1948–2012. We analyse observed early spring (March-April)

and late spring (May-June) NH SCE extent changes in these datasets using climate simulations of the responses to anthropogenic and natural forcings combined (ALL) and to natural forcings alone (NAT) from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The ALL-forcing response is detected in all of the observed records, indicating that observed changes are inconsistent with internal variability. The analysis also shows that the ALL-forcing simulations substantially underestimate the observed changes as recorded in the Brown and NOAA datasets, but that they are more consistent with changes seen in the GLDAS and 20CR2 reanalyses. A two-signal analysis of the GLDAS data is able to detect the influence of the anthropogenic component of the observed SCE changes separately from the effect of natural forcing. Despite dataset and modelling uncertainty, these results, together with the understanding of the causes of observed warming over the past century, provide substantial evidence of a human contribution to the observed decline in Northern Hemisphere spring snow cover extent.

Quiring, S. M., T. W. Ford, J. K. Wang, A. Khong, E. Harris, T. Lindgren, D. W. Goldberg, and Z. Li. 2016. **The North American Soil Moisture Database: development and applications.** Bulletin of the American Meteorological Society 97:1441-1459. http://doi:10.1175/BAMS-D-13-00263.1

Abstract. Soil moisture is an important variable in the climate system that integrates the combined influence of the atmosphere, land surface, and soil. Soil moisture is frequently used for drought monitoring and climate forecasting. However, in situ soil moisture observations are not systematically archived and there are relatively few national soil moisture networks. The lack of observed soil moisture data makes it difficult to characterize long-term soil moisture variability and trends. The North American Soil Moisture Database (NASMD) is a new high-quality observational soil moisture database. It includes over 1,800 monitoring stations in the United States, Canada, and Mexico, making it the largest collections of in situ soil moisture observations in North America. Data are collected from multiple sources, quality controlled, and integrated into an online database (soilmoisture.tamu.edu). Here we describe the development of the database, including quality control/quality assurance, standardization, and collection of metadata. The utility of the NASMD is demonstrated through an analysis of the inter- and intraannual variability of soil moisture from multiple networks. The NASMD is a useful tool for drought monitoring and forecasting, calibrating/validating satellites

and land surface models, and documenting how soil moisture influences the climate system on seasonal to interannual time scales.

Silverman, N. L., and M. P. Maneta. 2016. **Detectability of change in winter precipitation within mountain landscapes: Spatial patterns and uncertainty.** Water Resources Research 52:4301-4320. http://10.1002/2014WR016493

Abstract. Detecting long-term change in seasonal precipitation using ground observations is dependent on the representativity of the point measurement to the surrounding landscape. In mountainous regions, representativity can be poor and lead to large uncertainties in precipitation estimates at high elevations or in areas where observations are sparse. If the uncertainty in the estimate is large compared to the long-term shifts in precipitation, then the change will likely go undetected. In this analysis, we examine the minimum detectable change across mountainous terrain in western Montana, USA. We ask the question: What is the minimum amount of change that is necessary to be detected using our best estimates of precipitation in complex terrain? We evaluate the spatial uncertainty in the precipitation estimates by conditioning historic regional climate model simulations to ground observations using Bayesian inference. By using this uncertainty as a null hypothesis, we test for detectability across the study region. To provide context for the detectability calculations, we look at a range of future scenarios from the Coupled Model Intercomparison Project 5 (CMIP5) multimodel ensemble downscaled to 4 km resolution using the MACAv2-METDATA data set. When using the ensemble averages we find that approximately 65% of the significant increases in winter precipitation go undetected at midelevations. At high elevation, approximately 75% of significant increases in winter precipitation are undetectable. Areas where change can be detected are largely controlled by topographic features. Elevation and aspect are key characteristics that determine whether or not changes in winter precipitation can be detected. Furthermore, we find that undetected increases in winter precipitation at high elevation will likely remain as snow under climate change scenarios. Therefore, there is potential for these areas to offset snowpack loss at lower elevations and confound the effects of climate change on water resources.

Terrer, C., S. Vicca, B. A. Hungate, R. P. Phillips, and I. C. Prentice. 2016. **Mycorrhizal association as a primary control of the CO2 fertilization effect.** Science 353:72-74. http://10.1126/science.aaf4610

Abstract. Plants buffer increasing atmospheric carbon dioxide (CO_2) concentrations through enhanced growth, but the question whether nitrogen availability constrains the magnitude of this ecosystem service remains unresolved. Synthesizing experiments from around the world, we show that CO_2 fertilization is best explained by a simple interaction between nitrogen availability and mycorrhizal association. Plant species that associate with ectomycorrhizal fungi show a strong biomass increase (30 ± 3%, $P < 0.001$) in response to elevated CO_2 regardless of nitrogen availability, whereas low nitrogen availability limits CO_2 fertilization (0 ± 5%, $P = 0.946$) in plants that associate with arbuscular mycorrhizal fungi. The incorporation of mycorrhizae in global carbon cycle models is feasible, and crucial if we are to accurately project ecosystem responses and feedbacks to climate change.

Fire

Fischer, A. P., T. A. Spies, T. A. Steelman, C. Moseley, B. R. Johnson, J. D. Bailey, A. A. Ager, P. Bourgeron, S. Charnley, B. M. Collins, J. D. Kline, J. E. Leahy, J. S. Littell, J. D. A. Millington, M. Nielsen-Pincus, C. S. Olsen, T. B. Paveglio, Christopher I. Roos, M. M. Steen-Adams, F. R. Stevens, J. Vukomanovic, E. M. White, and D. M. J. S. Bowman. 2016. **Wildfire risk as a socioecological pathology.** Frontiers in Ecology and the Environment 14:276-284. http://10.1002/fee.1283

Abstract. Wildfire risk in temperate forests has become a nearly intractable problem that can be characterized as a socioecological “pathology”: that is, a set of complex and problematic interactions among social and ecological systems across multiple spatial and temporal scales. Assessments of wildfire risk could benefit from recognizing and accounting for these interactions in terms of socioecological systems, also known as coupled natural and human systems (CNHS). We characterize the primary social and ecological dimensions of the wildfire risk pathology, paying particular attention to the governance system around wildfire risk, and suggest strategies to mitigate the pathology through innovative planning approaches, analytical tools, and policies. We caution that even with a clear

understanding of the problem and possible solutions, the system by which human actors govern fire-prone forests may evolve incrementally in imperfect ways and can be expected to resist change even as we learn better ways to manage CNHS.

Knorr, W., A. Arneth, and L. Jiang. 2016. **Demographic controls of future global fire risk.** Nature Climate Change 6:781-785. http://10.1038/nclimate2999

Abstract. Wildfires are an important component of terrestrial ecosystem ecology but also a major natural hazard to societies, and their frequency and spatial distribution must be better understood. At a given location, risk from wildfire is associated with the annual fraction of burned area, which is expected to increase in response to climate warming. Until recently, however, only a few global studies of future fire have considered the effects of other important global environmental change factors such as atmospheric CO_2 levels and human activities, and how these influence fires in different regions. Here, we contrast the impact of climate change and increasing atmospheric CO_2 content on burned area with that of demographic dynamics, using ensembles of climate simulations combined with historical and projected population changes under different socio-economic development pathways for 1901–2100. Historically, humans notably suppressed wildfires. For future scenarios, global burned area will continue to decline under a moderate emissions scenario, except for low population growth and fast urbanization, but start to increase again from around mid-century under high greenhouse gas emissions. Contrary to common perception, we find that human exposure to wildfires increases in the future mainly owing to projected population growth in areas with frequent wildfires, rather than by a general increase in burned area.

Littell, J. S., D. L. Peterson, K. L. Riley, Y. Liu, and C. H. Luce. 2016. **A review of the relationships between drought and forest fire in the United States.** Global Change Biology 22:2353-2369. http://10.1111/gcb.13275

Abstract. The historical and presettlement relationships between drought and wildfire are well documented in North America, with forest fire occurrence and area clearly increasing in response to drought. There is also evidence that drought interacts with other controls (forest productivity, topography, fire weather, management activities) to affect fire intensity, severity, extent, and frequency. Fire regime

characteristics arise across many individual fires at a variety of spatial and temporal scales, so both weather and climate – including short- and long-term droughts – are important and influence several, but not all, aspects of fire regimes. We review relationships between drought and fire regimes in United States forests, fire-related drought metrics and expected changes in fire risk, and implications for fire management under climate change. Collectively, this points to a conceptual model of fire on real landscapes: fire regimes, and how they change through time, are products of fuels and how other factors affect their availability (abundance, arrangement, continuity) and flammability (moisture, chemical composition). Climate, management, and land use all affect availability, flammability, and probability of ignition differently in different parts of North America. From a fire ecology perspective, the concept of drought varies with scale, application, scientific or management objective, and ecosystem.

Sea Level Rise

Hauer, M. E., J. M. Evans, and D. R. Mishra. 2016. **Millions projected to be at risk from sea-level rise in the continental United States.** Nature Climate Change 6:691-695. http://10.1038/nclimate2961

Abstract. Sea-level rise (SLR) is one of the most apparent climate change stressors facing human society. Although it is known that many people at present inhabit areas vulnerable to SLR, few studies have accounted for ongoing population growth when assessing the potential magnitude of future impacts. Here we address this issue by coupling a small-area population projection with a SLR vulnerability assessment across all United States coastal counties. We find that a 2100 SLR of 0.9 m places a land area projected to house 4.2 million people at risk of inundation, whereas 1.8 m affects 13.1 million people—approximately two times larger than indicated by current populations. These results suggest that the absence of protective measures could lead to US population movements of a magnitude similar to the twentieth century Great Migration of southern African-Americans. Furthermore, our population projection approach can be readily adapted to assess other hazards or to model future per capita economic impacts.

Slangen, A. B. A., J. A. Church, C. Agosta, X. Fettweis, B. Marzeion, and K. Richter. 2016. **Anthropogenic forcing dominates global mean sea-level rise since 1970.** Nature Climate Change 6:701-705. http://10.1038/nclimate2991

Abstract. Sea-level change is an important consequence of anthropogenic climate change, as higher sea levels increase the frequency of sea-level extremes and the impact of coastal flooding and erosion on the coastal environment, infrastructure and coastal communities. Although individual attribution studies have been done for ocean thermal expansion and glacier mass loss, two of the largest contributors to twentieth-century sea-level rise, this has not been done for the other contributors or total global mean sea-level change (GMSLC). Here, we evaluate the influence of greenhouse gases (GHGs), anthropogenic aerosols, natural radiative forcings and internal climate variability on sea-level contributions of ocean thermal expansion, glaciers, ice-sheet surface mass balance and total GMSLC. For each contribution, dedicated models are forced with results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model archive. The sum of all included contributions explains 74 ± 22% (±2σ) of the observed GMSLC over the period 1900–2005. The natural radiative forcing makes essentially zero contribution over the twentieth century (2 ± 15% over the period 1900–2005), but combined with the response to past climatic variations explains 67 ± 23% of the observed rise before 1950 and only 9 ± 18% after 1970 (38 ± 12% over the period 1900–2005). In contrast, the anthropogenic forcing (primarily a balance between a positive sea-level contribution from GHGs and a partially offsetting component from anthropogenic aerosols) explains only 15 ± 55% of the observations before 1950, but increases to become the dominant contribution to sea-level rise after 1970 (69 ± 31%), reaching 72 ± 39% in 2000 (37 ± 38% over the period 1900–2005).

Adaptation

Butt, N., H. P. Possingham, C. De Los Rios, R. Maggini, R. A. Fuller, S. L. Maxwell, and J. E. M. Watson. 2016. **Challenges in assessing the vulnerability of species to climate change to inform conservation actions.** Biological Conservation 199:10-15. http://dx.doi.org/10.1016/j.biocon.2016.04.020

Abstract. Understanding climate change impacts on species is vital for correctly estimating their extinction risk and choosing appropriate

conservation actions. We perceive four common challenges that hamper conservation planning for species affected by climate change: (i) only considering climate exposure in assessments of vulnerability to climate change, ignoring the two other components of vulnerability (sensitivity and adaptive capacity); (ii) treating climate change as a long-term, gradual threat without recognising that it will change the frequency and magnitude of climate extremes; (iii) treating climate change as a future threat, disregarding current impacts of existing change; and, (iv) focusing on direct impacts of climate change, ignoring its interactions with other threats. We describe the implications of these challenges and urge that establishing management objectives in relation to species' vulnerability is crucial for choosing effective and efficient conservation action.

Esralew, R. A., L. Flint, J. H. Thorne, R. Boynton, and A. Flint. 2016. **A framework for effective use of hydroclimate models in climate-change adaptation planning for managed habitats with limited hydrologic response data.** Environmental Management 58:60-75. http://10.1007/s00267-015-0569-y

Abstract. Climate-change adaptation planning for managed wetlands is challenging under uncertain futures when the impact of historic climate variability on wetland response is unquantified. We assessed vulnerability of Modoc National Wildlife Refuge (MNWR) through use of the Basin Characterization Model (BCM) landscape hydrology model, and six global climate models, representing projected wetter and drier conditions. We further developed a conceptual model that provides greater value for water managers by incorporating the BCM outputs into a conceptual framework that links modeled parameters to refuge management outcomes. This framework was used to identify landscape hydrology parameters that reflect refuge sensitivity to changes in (1) climatic water deficit (CWD) and recharge, and (2) the magnitude, timing, and frequency of water inputs. BCM outputs were developed for 1981–2100 to assess changes and forecast the probability of experiencing wet and dry water year types that have historically resulted in challenging conditions for refuge habitat management. We used a Yule’s Q skill score to estimate the probability of modeled discharge that best represents historic water year types. CWD increased in all models across 72.3–100 % of the water supply basin by 2100. Earlier timing in discharge, greater cool season discharge, and lesser irrigation season water supply were predicted by most models. Under the worst-case scenario, moderately dry years increased from 10–20 to 40–60 % by 2100. MNWR could adapt by

storing additional water during the cool season for later use and prioritizing irrigation of habitats during dry years.

Huntingford, C., and L. M. Mercado. 2016. **High chance that current atmospheric greenhouse concentrations commit to warmings greater than 1.5 °C over land.** Scientific Reports 6:30294. http://10.1038/srep30294

Abstract. The recent Paris UNFCCC climate meeting discussed the possibility of limiting global warming to 2 °C since pre-industrial times, or possibly even 1.5 °C, which would require major future emissions reductions. However, even if climate is stabilised at current atmospheric greenhouse gas (GHG) concentrations, those warming targets would almost certainly be surpassed in the context of mean temperature increases over land only. The reason for this is two-fold. First, current transient warming lags significantly below equilibrium or "committed" warming. Second, almost all climate models indicate warming rates over land are much higher than those for the oceans. We demonstrate this potential for high eventual temperatures over land, even for contemporary GHG levels, using a large set of climate models and for which climate sensitivities are known. Such additional land warming has implications for impacts on terrestrial ecosystems and human well-being. This suggests that even if massive and near-immediate emissions reductions occur such that atmospheric GHGs increase further by only small amounts, careful planning is needed by society to prepare for higher land temperatures in an eventual equilibrium climatic state.

Mitigation

Dilling, L., K. C. Kelsey, D. P. Fernandez, Y. D. Huang, J. B. Milford, and J. C. Neff. 2016. **Managing carbon on federal public lands: opportunities and challenges in southwestern Colorado.** Environmental Management 58:283-296. http://10.1007/s00267-016-0714-2

Abstract. Federal lands in the United States have been identified as important areas where forests could be managed to enhance carbon storage and help mitigate climate change. However, there has been little work examining the context for decision making for carbon in a multiple-use public land environment, and how science can support decision making. This case study of the San Juan National Forest and

the Bureau of Land Management Tres Rios Field Office in southwestern Colorado examines whether land managers in these offices have adequate tools, information, and management flexibility to practice effective carbon stewardship. To understand how carbon was distributed on the management landscape we added a newly developed carbon map for the SJNF–TRFO area based on Landsat TM texture information (Kelsey and Neff in Remote Sens 6:6407–6422. doi: 10.3390/rs6076407, 2014). We estimate that only about 22 % of the aboveground carbon in the SJNF–TRFO is in areas designated for active management, whereas about 38 % is in areas with limited management opportunities, and 29 % is in areas where natural processes should dominate. To project the effects of forest management actions on carbon storage, staff of the SJNF are expected to use the Forest Vegetation Simulator (FVS) and extensions. While identifying FVS as the best tool generally available for this purpose, the users and developers we interviewed highlighted the limitations of applying an empirically based model over long time horizons. Future research to improve information on carbon storage should focus on locations and types of vegetation where carbon management is feasible and aligns with other management priorities.

McGuire, J. L., J. J. Lawler, B. H. McRae, T. A. Nuñez, and D. M. Theobald. 2016. **Achieving climate connectivity in a fragmented landscape.** Proceedings of the National Academy of Sciences 113:7195-7200. http://10.1073/pnas.1602817113

Abstract. The contiguous United States contains a disconnected patchwork of natural lands. This fragmentation by human activities limits species' ability to track suitable climates as they rapidly shift. However, most models that project species movement needs have not examined where fragmentation will limit those movements. Here, we quantify climate connectivity, the capacity of landscape configuration to allow species movement in the face of dynamically shifting climate. Using this metric, we assess to what extent habitat fragmentation will limit species movements in response to climate change. We then evaluate how creating corridors to promote climate connectivity could potentially mitigate these restrictions, and we assess where strategies to increase connectivity will be most beneficial. By analyzing fragmentation patterns across the contiguous United States, we demonstrate that only 41% of natural land area retains enough connectivity to allow plants and animals to maintain climatic parity as the climate warms. In the eastern United States, less than 2% of natural area is sufficiently connected. Introducing corridors to facilitate movement through human-dominated regions increases the percentage of climatically connected natural area to 65%, with the most impactful gains in low-elevation regions, particularly in the southeastern United States. These climate connectivity analyses allow ecologists and conservation practitioners to determine the most effective regions for increasing connectivity. More importantly, our findings demonstrate that increasing climate connectivity is critical for allowing species to track rapidly changing climates, reconfiguring habitats to promote access to suitable climates.

Climate Education

Walton, P. J., M. B. Yarker, M. D. S. Mesquita, and F. E. L. Otto. 2016. **Helping to make sense of regional climate modeling: professional development for scientists and decision-makers anytime, anywhere.** Bulletin of the American Meteorological Society 97:1173-1185. http://doi:10.1175/BAMS-D-14-00111.1

Abstract. Globally, decision-makers are increasingly using high-resolution climate models to support policy and planning; however, many of these users do not have the knowledge needed to use them appropriately. This problem is compounded by not having access to quality learning opportunities to better understand how to apply the models and interpret results. This paper discusses and proposes an educational framework based on two independent online courses on regional climate modeling, which addresses the accessibility issue and provides guidance to climate science professors, researchers, and institutions who want to create their own online courses.The role of e-learning as an educational tool is well documented, highlighting the benefits of improved personal efficiency through “anywhere, anytime” learning with the flexibility to support professional development across different sectors. In addition, improved global Internet means increased accessibility. However, e-learning’s function as a tool to support understanding of atmospheric physics and high-resolution climate modeling has not been widely discussed. To date, few courses, if any, support understanding that takes full advantage of e-learning best practices.There is a growing need for climate literacy to help inform decision-making on a range of scales, from individual households to corporate CEOs. And while there is a plethora of climate information online, educational theory suggests that people need to be guided in how to convert this information into applicable knowledge.Here, we present how the experience of the courses we

designed and ran independent of each other, both engaging learners with better understanding benefits and limitations of regional climate modeling, lead to a framework of designing e-learning for climate modeling.