Climate Change Quarterly: Summer 2015

Abstracts of Recent Papers on Climate Change and Land Management in the West

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Climate Projections

Dai, A., J. C. Fyfe, S.-P. Xie, and X. Dai. 2015. **Decadal modulation of global surface temperature by internal climate variability.** Nature Climate Change 5:555-559.

Abstract. Despite a steady increase in atmospheric greenhouse gases (GHGs), global-mean surface temperature (T) has shown no discernible warming since about 2000, in sharp contrast to model simulations, which on average project strong warming. The recent slowdown in observed surface warming has been attributed to decadal cooling in the tropical Pacific, intensifying trade winds, changes in El Niño activity, increasing volcanic activity and decreasing solar irradiance. Earlier periods of arrested warming have been observed but received much less attention than the recent period, and their causes are poorly understood. Here we analyse observed and model-simulated global T fields to quantify the contributions of internal climate variability (ICV) to decadal changes in global-mean T since 1920. We show that the Interdecadal Pacific Oscillation (IPO) has been associated with large T anomalies over both ocean and land. Combined with another leading mode of ICV, the IPO explains most of the difference between observed and model-simulated rates of decadal change in global-mean T since 1920, and particularly over the so-called 'hiatus' period since about 2000. We conclude that ICV, mainly through the IPO, was largely responsible for the recent slowdown, as well as for earlier slowdowns and accelerations in global-mean T since 1920, with preferred spatial patterns different from those associated with GHG-induced warming or aerosol-induced cooling. Recent history suggests that the IPO could reverse course and lead to accelerated global warming in the coming decades.

Greve, P., and S. I. Seneviratne. 2015. **Assessment of future changes in water availability and aridity.** Geophysical Research Letters 42:2015GL064127.

Abstract. Substantial changes in the hydrological cycle are projected for the 21st century, but these projections are subject to major uncertainties. In this context, the “dry gets drier, wet gets wetter” (DDWW) paradigm is often used as a simplifying summary. However, recent studies cast doubt on the validity of the paradigm and also on applying the widely used P – E (precipitation – evapotranspiration) metric over global land surfaces. Here we show in a comprehensive CMIP5-based assessment that projected changes in mean annual P – E are generally not significant, except for high-latitude regions showing wetting conditions until the end of the 21st century. Significant increases in aridity do occur in many subtropical and also adjacent humid regions. However, combining both metrics still shows that approximately 70% of all land area will not experience significant changes. Based on these findings, we conclude that the DDWW paradigm is generally not confirmed for projected changes in most land areas.

Karl, T. R., A. Arguez, B. Huang, J. H. Lawrimore, J. R. McMahon, M. J. Menne, T. C. Peterson, R. S. Vose, and H.-M. Zhang. 2015. **Possible artifacts of data biases in the recent global surface warming hiatus.** Science 348:1469-1472.

Abstract. Much study has been devoted to the possible causes of an apparent decrease in the upward trend of global surface temperatures since 1998, a phenomenon that has been dubbed the global warming “hiatus.” Here, we present an updated global surface temperature analysis that reveals that global trends are higher than those reported by the Intergovernmental Panel on Climate Change, especially in recent decades, and that the central estimate for the rate of warming during the first 15 years of the 21st century is at least as great as the last half of the 20th century. These results do not support the notion of a “slowdown” in the increase of global surface temperature.

Knapp, A. K., D. L. Hoover, K. R. Wilcox, M. L. Avolio, S. E. Koerner, K. J. La Pierre, M. E. Loik, Y. Luo, O. E. Sala, and M. D. Smith. 2015. **Characterizing differences in precipitation regimes of extreme wet and dry years: implications for climate change experiments.** Global Change Biology 21:2624-2633.

Abstract. Climate change is intensifying the hydrologic cycle and is expected to increase the frequency of extreme wet and dry years. Beyond precipitation amount, extreme wet and dry years may differ in other ways, such as the number of precipitation events, event size, and the time between events. We assessed 1614 long-term (100 year) precipitation records from around the world to identify key attributes of precipitation regimes, besides amount, that distinguish statistically extreme wet from extreme dry years. In general, in regions where mean annual precipitation (MAP) exceeded 1000 mm, precipitation amounts in extreme wet and dry years differed from average years by ~40% and 30%, respectively. The magnitude of these deviations increased to >60% for dry years and to >150% for wet years in arid regions (MAP<500 mm). Extreme wet years were primarily distinguished from average and extreme dry years by the presence of multiple extreme (large) daily precipitation events (events >99th percentile of all events); these occurred twice as often in extreme wet years compared to average years. In contrast, these large precipitation events were rare in extreme dry years. Less important for distinguishing extreme wet from dry years were mean event size and frequency, or the number of dry days between events. However, extreme dry years were distinguished from average years by an increase in the number of dry days between events. These precipitation regime attributes consistently differed between extreme wet and dry years across 12 major terrestrial ecoregions from around the world, from deserts to the tropics. Thus, we recommend that climate change experiments and model simulations incorporate these differences in key precipitation regime attributes, as well as amount into treatments. This will allow experiments to more realistically simulate extreme precipitation years and more accurately assess the ecological consequences.

Monier, E., and X. Gao. 2015. **Climate change impacts on extreme events in the United States: an uncertainty analysis.** Climatic Change 131:67-81.

Abstract. In this study, we analyze changes in extreme temperature and precipitation over the US in a 60-member ensemble simulation of the 21st century with the Massachusetts Institute of Technology (MIT)

Integrated Global System Model–Community Atmosphere Model (IGSM-CAM). Four values of climate sensitivity, three emissions scenarios and five initial conditions are considered. The results show a general intensification and an increase in the frequency of extreme hot temperatures and extreme precipitation events over most of the US. Extreme cold temperatures are projected to decrease in intensity and frequency, especially over the northern parts of the US. This study displays a wide range of future changes in extreme events in the US, even simulated by a single climate model. Results clearly show that the choice of policy is the largest source of uncertainty in the magnitude of the changes. The impact of the climate sensitivity is largest for the unconstrained emissions scenario and the implementation of a stabilization scenario drastically reduces the changes in extremes, even for the highest climate sensitivity considered. Finally, simulations with different initial conditions show conspicuously different patterns and magnitudes of changes in extreme events, underlining the role of natural variability in projections of changes in extreme events.

Monier, E., X. Gao, J. Scott, A. Sokolov, and C. A. Schlosser. 2015. **A framework for modeling uncertainty in regional climate change.** Climatic Change 131:51-66.

Abstract. In this study, we present a new modeling framework and a large ensemble of climate projections to investigate the uncertainty in regional climate change over the United States (US) associated with four dimensions of uncertainty. The sources of uncertainty considered in this framework are the emissions projections, global climate system parameters, natural variability and model structural uncertainty. The modeling framework revolves around the Massachusetts Institute of Technology (MIT) Integrated Global System Model (IGSM), an integrated assessment model with an Earth System Model of Intermediate Complexity (EMIC) (with a two-dimensional zonal-mean atmosphere). Regional climate change over the US is obtained through a two-pronged approach. First, we use the IGSM-CAM framework, which links the IGSM to the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM). Second, we use a pattern-scaling method that extends the IGSM zonal mean based on climate change patterns from various climate models. Results show that the range of annual mean temperature changes are mainly driven by policy choices and the range of climate sensitivity considered. Meanwhile, the four sources of uncertainty contribute more equally to end-of-century precipitation changes, with natural variability dominating until 2050. For the set of scenarios used in this study, the

choice of policy is the largest driver of uncertainty, defined as the range of warming and changes in precipitation, in future projections of climate change over the US.

Nieves, V., J. K. Willis, and W. C. Patzert. 2015. **Recent hiatus caused by decadal shift in Indo-Pacific heating.** Science 349:532-535.

Abstract. Recent modeling studies have proposed different scenarios to explain the slowdown in surface temperature warming in the most recent decade. Some of these studies seem to support the idea of internal variability and/or rearrangement of heat between the surface and the ocean interior. Others suggest that radiative forcing might also play a role. Our examination of observational data over the past two decades shows some significant differences when compared to model results from reanalyses and provides the most definitive explanation of how the heat was redistributed. We find that cooling in the top 100-meter layer of the Pacific Ocean was mainly compensated for by warming in the 100- to 300-meter layer of the Indian and Pacific Oceans in the past decade since 2003.

Schurer, A. P., G. C. Hegerl, and S. P. Obrochta. 2015. **Determining the likelihood of pauses and surges in global warming.** Geophysical Research Letters 42:5974-5982.

Abstract. The recent warming “hiatus” is subject to intense interest, with proposed causes including natural forcing and internal variability. Here we derive samples of all natural and internal variability from observations and a recent proxy reconstruction to investigate the likelihood that these two sources of variability could produce a hiatus or rapid warming in surface temperature. The likelihood is found to be consistent with that calculated previously for models and exhibits a similar spatial pattern, with an Interdecadal Pacific Oscillation-like structure, although with more signal in the Atlantic than in model patterns. The number and length of events increases if natural forcing is also considered, particularly in the models. From the reconstruction it can be seen that large eruptions, such as Mount Tambora in 1815, or clusters of eruptions, may result in a hiatus of over 20 years, a finding supported by model results.

Smith, K., C. Strong, and S.-Y. Wang. 2015. **Connectivity between Historical Great Basin Precipitation and Pacific Ocean Variability: A CMIP5 Model Evaluation.** Journal of Climate 28:6096-6112.

Abstract. The eastern Great Basin (GB) in the western United States is strongly affected by droughts that influence water management decisions. Precipitation that falls in the GB, particularly in the Great Salt Lake (GSL) basin encompassed by the GB, provides water for millions of people living along the Wasatch Front Range. Western U.S. precipitation is known to be influenced by El Niño–Southern Oscillation (ENSO) as well as the Pacific decadal oscillation (PDO) in the North Pacific. Historical connectivity between GB precipitation and Pacific Ocean sea surface temperatures (SSTs) on interannual to multidecadal time scales is evaluated for 20 models that participated in phase 5 of the Coupled Model Intercomparison Project (CMIP5). While the majority of the models had realistic ENSO and PDO spatial patterns in the SSTs, the simulated influence of these two modes on GB precipitation tended to be too strong for ENSO and too weak for PDO. Few models captured the connectivity at a quasi-decadal period influenced by the transition phase of the Pacific quasi-decadal oscillation (QDO; a recently identified climate mode that influences GB precipitation). Some of the discrepancies appear to stem from models not capturing the observed tendency for the PDO to modulate the sign of the ENSO–GB precipitation teleconnection. Of all of the models, CCSM4 most consistently captured observed connections between Pacific SST variability and GB precipitation on the examined time scales.

Vano, J. A., J. B. Kim, D. E. Rupp, and P. W. Mote. 2015. **Selecting climate change scenarios using impact-relevant sensitivities.** Geophysical Research Letters 42:2015GL063208.

Abstract. Climate impact studies often require the selection of a small number of climate scenarios. Ideally, a subset would have simulations that both (1) appropriately represent the range of possible futures for the variable/s most important to the impact under investigation and (2) come from global climate models (GCMs) that provide plausible results for future climate in the region of interest. We demonstrate an approach to select a subset of GCMs that incorporates both concepts and provides insights into the range of climate impacts. To represent how an ecosystem process responds to projected future changes, we methodically sample, using a simple sensitivity analysis, how an ecosystem variable responds locally to projected regional temperature

and precipitation changes. We illustrate our approach in the Pacific Northwest, focusing on (a) changes in streamflow magnitudes in critical seasons for water management and (b) changes in annual vegetation carbon.

Carbon and Carbon Storage

Farrior, C. E., I. Rodriguez-Iturbe, R. Dybzinski, S. A. Levin, and S. W. Pacala. 2015. **Decreased water limitation under elevated CO2 amplifies potential for forest carbon sinks.** Proceedings of the National Academy of Sciences 112:7213-7218.

Abstract. Increasing atmospheric CO_2 concentrations and changing rainfall regimes are creating novel environments for plant communities around the world. The resulting changes in plant productivity and allocation among tissues will have significant impacts on forest carbon storage and the global carbon cycle, yet these effects may depend on mechanisms not included in global models. Here we focus on the role of individual-level competition for water and light in forest carbon allocation and storage across rainfall regimes. We find that the complexity of plant responses to rainfall regimes in experiments can be explained by individual-based competition for water and light within a continuously varying soil moisture environment. Further, we find that elevated CO_2 leads to large amplifications of carbon storage when it alleviates competition for water by incentivizing competitive plants to divert carbon from short-lived fine roots to long-lived woody biomass. Overall, we find that plant dependence on rainfall regimes and plant responses to added CO_2 are complex, but understandable. The insights developed here will serve as an important foundation as we work to predict the responses of plants to the full, multidimensional reality of climate change, which involves not only changes in rainfall and CO_2 but also changes in temperature, nutrient availability, and disturbance rates, among others.

Frank, D., M. Reichstein, M. Bahn, K. Thonicke, D. Frank, M. D. Mahecha, P. Smith, M. van der Velde, S. Vicca, F. Babst, C. Beer, N. Buchmann, J. G. Canadell, P. Ciais, W. Cramer, A. Ibrom, F. Miglietta, B. Poulter, A. Rammig, S. I. Seneviratne, A. Walz, M. Wattenbach, M. A. Zavala, and J. Zscheischler. 2015. **Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts.** Global Change Biology 21:2861-2880.

Abstract. Extreme droughts, heat waves, frosts, precipitation, wind storms and other climate extremes may impact the structure, composition and functioning of terrestrial ecosystems, and thus carbon cycling and its feedbacks to the climate system. Yet, the interconnected avenues through which climate extremes drive ecological and physiological processes and alter the carbon balance are poorly understood. Here, we review the literature on carbon cycle relevant responses of ecosystems to extreme climatic events. Given that impacts of climate extremes are considered disturbances, we assume the respective general disturbance-induced mechanisms and processes to also operate in an extreme context. The paucity of well-defined studies currently renders a quantitative meta-analysis impossible, but permits us to develop a deductive framework for identifying the main mechanisms (and coupling thereof) through which climate extremes may act on the carbon cycle. We find that ecosystem responses can exceed the duration of the climate impacts via lagged effects on the carbon cycle. The expected regional impacts of future climate extremes will depend on changes in the probability and severity of their occurrence, on the compound effects and timing of different climate extremes, and on the vulnerability of each land-cover type modulated by management. Although processes and sensitivities differ among biomes, based on expert opinion, we expect forests to exhibit the largest net effect of extremes due to their large carbon pools and fluxes, potentially large indirect and lagged impacts, and long recovery time to regain previous stocks. At the global scale, we presume that droughts have the strongest and most widespread effects on terrestrial carbon cycling. Comparing impacts of climate extremes identified via remote sensing vs. ground-based observational case studies reveals that many regions in the (sub-)tropics are understudied. Hence, regional investigations are needed to allow a global upscaling of the impacts of climate extremes on global carbon–climate feedbacks.

Hararuk, O., M. J. Smith, and Y. Luo. 2015. **Microbial models with data-driven parameters predict stronger soil carbon responses to climate change.** Global Change Biology 21:2439-2453.

Abstract. Long-term carbon (C) cycle feedbacks to climate depend on the future dynamics of soil organic carbon (SOC). Current models show low predictive accuracy at simulating contemporary SOC pools, which can be improved through parameter estimation. However, major uncertainty remains in global soil responses to climate change, particularly uncertainty in how the activity of soil microbial communities will respond. To date, the role of microbes in SOC dynamics has been implicitly described by decay rate constants in most conventional global carbon cycle models. Explicitly including microbial biomass dynamics into C cycle model formulations has shown potential to improve model predictive performance when assessed against global SOC databases. This study aimed to data-constrained parameters of two soil microbial models, evaluate the improvements in performance of those calibrated models in predicting contemporary carbon stocks, and compare the SOC responses to climate change and their uncertainties between microbial and conventional models. Microbial models with calibrated parameters explained 51% of variability in the observed total SOC, whereas a calibrated conventional model explained 41%. The microbial models, when forced with climate and soil carbon input predictions from the 5th Coupled Model Intercomparison Project (CMIP5), produced stronger soil C responses to 95 years of climate change than any of the 11 CMIP5 models. The calibrated microbial models predicted between 8% (2-pool model) and 11% (4-pool model) soil C losses compared with CMIP5 model projections which ranged from a 7% loss to a 22.6% gain. Lastly, we observed unrealistic oscillatory SOC dynamics in the 2-pool microbial model. The 4-pool model also produced oscillations, but they were less prominent and could be avoided, depending on the parameter values.

Mills, D., R. Jones, K. Carney, A. St. Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, and E. Monier. 2015. **Quantifying and monetizing potential climate change policy impacts on terrestrial ecosystem carbon storage and wildfires in the United States.** Climatic Change 131:163-178.

Abstract. This paper develops and applies methods to quantify and monetize projected impacts on terrestrial ecosystem carbon storage

and areas burned by wildfires in the contiguous United States under scenarios with and without global greenhouse gas mitigation. The MC1 dynamic global vegetation model is used to develop physical impact projections using three climate models that project a range of future conditions. We also investigate the sensitivity of future climates to different initial conditions of the climate model. Our analysis reveals that mitigation, where global radiative forcing is stabilized at 3.7 W/m2 in 2100, would consistently reduce areas burned from 2001 to 2100 by tens of millions of hectares. Monetized, these impacts are equivalent to potentially avoiding billions of dollars (discounted) in wildfire response costs. Impacts to terrestrial ecosystem carbon storage are less uniform, but changes are on the order of billions of tons over this time period. The equivalent social value of these changes in carbon storage ranges from hundreds of billions to trillions of dollars (discounted). The magnitude of these results highlights their importance when evaluating climate policy options. However, our results also show national outcomes are driven by a few regions and results are not uniform across regions, time periods, or models. Differences in the results based on the modeling approach and across initializing conditions also raise important questions about how variability in projected climates is accounted for, especially when considering impacts where extreme or threshold conditions are important.

Russell, M. B., S. Fraver, T. Aakala, J. H. Gove, C. W. Woodall, A. W. D'Amato, and M. J. Ducey. 2015. **Quantifying carbon stores and decomposition in dead wood: A review.** Forest Ecology and Management 350:107-128.

Abstract. The amount and dynamics of forest dead wood (both standing and downed) has been quantified by a variety of approaches throughout the forest science and ecology literature. Differences in the sampling and quantification of dead wood can lead to differences in our understanding of forests and their role in the sequestration and emissions of CO_2, as well as in developing appropriate strategies for achieving dead wood-related objectives, including biodiversity protection, and procurement of forest bioenergy feedstocks. A thorough understanding of the various methods available for quantifying dead wood stores and decomposition is critical for comparing studies and drawing valid conclusions. General assessments of forest dead wood are conducted by numerous countries as a part of their national forest inventories, while detailed experiments that employ field-based and modeling methods to understand woody debris patterns and processes have greatly advanced our understanding of

dead wood dynamics. We review methods for quantifying dead wood in forest ecosystems, with an emphasis on biomass and carbon attributes. These methods encompass various sampling protocols for inventorying standing dead trees and downed woody debris, and an assortment of approaches for forecasting wood decomposition through time. Recent research has provided insight on dead wood attributes related to biomass and carbon content, through the use of structural reduction factors and robust modeling approaches, both of which have improved our understanding of dead wood dynamics. Our review, while emphasizing temperate forests, identifies key research needs and knowledge which at present impede our ability to accurately characterize dead wood populations. In sum, we synthesize the current literature on the measurement and dynamics of forest dead wood carbon stores and decomposition as a baseline for researchers and natural resource managers concerned about forest dead wood patterns and processes.

Verheijen, L. M., R. Aerts, V. Brovkin, J. Cavender-Bares, J. H. C. Cornelissen, J. Kattge, and P. M. van Bodegom. 2015. **Inclusion of ecologically based trait variation in plant functional types reduces the projected land carbon sink in an earth system model.** Global Change Biology 21:3074-3086.

Abstract. Earth system models demonstrate large uncertainty in projected changes in terrestrial carbon budgets. The lack of inclusion of adaptive responses of vegetation communities to the environment has been suggested to hamper the ability of modeled vegetation to adequately respond to environmental change. In this study, variation in functional responses of vegetation has been added to an earth system model (ESM) based on ecological principles. The restriction of viable mean trait values of vegetation communities by the environment, called ‘habitat filtering’, is an important ecological assembly rule and allows for determination of global scale trait–environment relationships. These relationships were applied to model trait variation for different plant functional types (PFTs). For three leaf traits (specific leaf area, maximum carboxylation rate at 25 °C, and maximum electron transport rate at 25 °C), relationships with multiple environmental drivers, such as precipitation, temperature, radiation, and CO_2, were determined for the PFTs within the Max Planck Institute ESM. With these relationships, spatiotemporal variation in these formerly fixed traits in PFTs was modeled in global change projections (IPCC RCP8.5 scenario). Inclusion of this environment-driven trait variation resulted in a strong reduction of the global carbon sink by at least 33% (2.1 Pg C yr^{-1}) from the 2nd quarter of the 21st century

onward compared to the default model with fixed traits. In addition, the mid- and high latitudes became a stronger carbon sink and the tropics a stronger carbon source, caused by trait-induced differences in productivity and relative respirational costs. These results point toward a reduction of the global carbon sink when including a more realistic representation of functional vegetation responses, implying more carbon will stay airborne, which could fuel further climate change.

Phenology Changes

Cayton, H. L., N. M. Haddad, K. Gross, S. E. Diamond, and L. Ries. 2015. **Do growing degree days predict phenology across butterfly species?** Ecology 96:1473-1479.

Abstract. Global climate change is causing shifts in phenology across multiple species. We use a geographically and temporally extensive data set of butterfly abundance across the state of Ohio to ask whether phenological change can be predicted from climatological data. Our focus is on growing degree days (GDD), a commonly used measure of thermal accumulation, as the mechanistic link between climate change and species phenology. We used simple calculations of median absolute error associated with GDD and an alternative predictor of phenology, ordinal date, for both first emergence and peak abundance of 13 butterfly species. We show that GDD acts as a better predictor than date for first emergence in nearly all species, and for peak abundance in more than half of all species, especially univoltine species. Species with less ecological flexibility, in particular those with greater dietary specialization, had greater predictability with GDD. The new method we develop for predicting phenology using GDD offers a simple yet effective way to predict species' responses to climate change.

Fu, Y. H., S. Piao, Y. Vitasse, H. Zhao, H. J. De Boeck, Q. Liu, H. Yang, U. Weber, H. Hänninen, and I. A. Janssens. 2015. **Increased heat requirement for leaf flushing in temperate woody species over 1980–2012: effects of chilling, precipitation and insolation.** Global Change Biology 21:2687-2697.

Abstract. Recent studies have revealed large unexplained variation in heat requirement-based phenology models, resulting in large uncertainty when predicting ecosystem carbon and water balance responses to climate variability. Improving our understanding of the

heat requirement for spring phenology is thus urgently needed. In this study, we estimated the species-specific heat requirement for leaf flushing of 13 temperate woody species using long-term phenological observations from Europe and North America. The species were defined as early and late flushing species according to the mean date of leaf flushing across all sites. Partial correlation analyses were applied to determine the temporal correlations between heat requirement and chilling accumulation, precipitation and insolation sum during dormancy. We found that the heat requirement for leaf flushing increased by almost 50% over the study period 1980–2012, with an average of 30 heat units per decade. This temporal increase in heat requirement was observed in all species, but was much larger for late than for early flushing species. Consistent with previous studies, we found that the heat requirement negatively correlates with chilling accumulation. Interestingly, after removing the variation induced by chilling accumulation, a predominantly positive partial correlation exists between heat requirement and precipitation sum, and a predominantly negative correlation between heat requirement and insolation sum. This suggests that besides the well-known effect of chilling, the heat requirement for leaf flushing is also influenced by precipitation and insolation sum during dormancy. However, we hypothesize that the observed precipitation and insolation effects might be artefacts attributable to the inappropriate use of air temperature in the heat requirement quantification. Rather than air temperature, meristem temperature is probably the prominent driver of the leaf flushing process, but these data are not available. Further experimental research is thus needed to verify whether insolation and precipitation sums directly affect the heat requirement for leaf flushing.

Keenan, T. F., and A. D. Richardson. 2015. **The timing of autumn senescence is affected by the timing of spring phenology: implications for predictive models.** Global Change Biology 21:2634-2641.

Abstract. Autumn senescence regulates multiple aspects of ecosystem function, along with associated feedbacks to the climate system. Despite its importance, current understanding of the drivers of senescence is limited, leading to a large spread in predictions of how the timing of senescence, and thus the length of the growing season, will change under future climate conditions. The most commonly held paradigm is that temperature and photoperiod are the primary controls, which suggests a future extension of the autumnal growing season as global temperatures rise. Here, using two decades of

ground- and satellite-based observations of temperate deciduous forest phenology, we show that the timing of autumn senescence is correlated with the timing of spring budburst across the entire eastern United States. On a year-to-year basis, an earlier/later spring was associated with an earlier/later autumn senescence, both for individual species and at a regional scale. We use the observed relationship to develop a novel model of autumn phenology. In contrast to current phenology models, this model predicts that the potential response of autumn phenology to future climate change is strongly limited by the impact of climate change on spring phenology. Current models of autumn phenology therefore may overpredict future increases in the length of the growing season, with subsequent impacts for modeling future CO2 uptake and evapotranspiration.

Species Range Changes

Case, M. J., J. J. Lawler, and J. A. Tomasevic. 2015. **Relative sensitivity to climate change of species in northwestern North America.** Biological Conservation 187:127-133.

Abstract. Climate change affects plants and animals in myriad ways and to different degrees. Therefore, managing species in the face of climate change will require an understanding of which species will be most sensitive to future climatic changes and what factors will make them more sensitive. The inherent sensitivity of species to climate change is influenced by many factors, including physiology, life-history traits, interspecific relationships, habitat associations, and relationships with disturbance regimes. Using a combination of scientific literature and expert knowledge, we assessed the relative sensitivity to climate change of 195 plant and animal species in the northwestern North America. We found that although there were highly sensitive species in each of the taxonomic groups analyzed, amphibians and reptiles were, as a group, estimated to be the most sensitive to climate change. Not surprisingly, we found that the confidence that experts had in their assessments varied by species. Our results also indicate that many species will be sensitive to climate change largely because they depend on habitats that will likely be significantly altered as climates change. Although to date, many climate impact assessments for species have focused on projecting range shifts, quantifying physiological limits, and assessing phenological shifts, in light of our results, a renewed emphasis on the collection of basic natural history data could go a long way toward

improving our ability to anticipate future climate impacts. Our results highlight the potential for basic information about climate-change sensitivity to facilitate the prioritization of management actions and research needs in the face of limited budgets.

Copeland, S. M., and S. P. Harrison. 2015. **Identifying plant traits associated with topographic contrasts in a rugged and diverse region (Klamath-Siskiyou Mts, OR, USA).** Ecography 38:569-577.

Abstract. Rugged topography affects species distributions and community composition by creating contrasting mesic (cool, moist) and xeric (warm, dry) microclimates on adjacent slopes. This microclimatic heterogeneity is thought to have contributed to species survival during past climate fluctuations. Within a rugged and botanically rich region, we asked what functional, distributional, and/or biogeographic traits distinguished the species significantly associated with xeric or mesic microclimates. For each of 236 species in 4773 plots in the Klamath-Siskiyou Mountains, we tested for significant associations with mesic or xeric topographic microclimates inferred from high-resolution topographic variables. For the subset of species showing significant associations, we then compared their functional traits, biogeographic origins, and macroclimatic attributes to those of other species. We also tested the dependence of topographic associations on elevation, canopy cover, and soil type. Many species in the region (40%) showed significant tendencies to be found only in either mesic or xeric topography. 'Mesic' species tended to be of northern biogeographic origin and to have geographic ranges with higher mean precipitation; 'xeric' species had the opposite attributes. Species occurred more often in mesic microclimates when they occurred on low-nutrient serpentine soils, and were more often found in xeric microclimates at high elevations. Functional traits such as specific leaf area were not significant predictors of species association with topographic microclimate. Biogeographic origins and the mean precipitation (rather than temperature) of species geographic ranges are the best indicators of species that are found in cool/moist northerly or hot/dry southerly microclimates.

Santos, M. J., J. H. Thorne, and C. Moritz. 2015. **Synchronicity in elevation range shifts among small mammals and vegetation over the last century is stronger for omnivores.** Ecography 38:556-568.

Abstract. In mountain ecosystems, species can be said to respond synchronously to environmental change when the elevation ranges of vegetation types and their associated vertebrates expand or contract in the same direction. Conversely, the response is asynchronous when the elevation ranges of vegetation types and associated vertebrates change in different directions. The capacity of vertebrate species to respond synchronously with change in the elevation ranges of the vegetation that comprises their habitat is likely a function of their ecological traits. Here we combine measures of elevation range shifts in 23 vertebrate species with those of their associated vegetation types across 80 yr, on a large elevation transect in California's Sierra Nevada mountains that encompasses Yosemite National Park. Half the species' shifts were synchronous with vegetation shifts, ¼ of the species were asynchronous, and the others showed no relationship. Most species that responded synchronously to changes in vegetation elevation ranges expanded their elevation range, and are inhabitants of low and intermediate elevations. In contrast, those species whose range shifts were asynchronous to associated vegetation shifts inhabit high elevations. These species experienced contraction in elevation range even while their associated vegetation types expanded. However, these species were responding synchronously to a subset of their associated vegetation types. Considering trait-based predictors, omnivores were more synchronous than herbivores. Our results on synchronous and asynchronous elevation shifts with vegetation may permit more accurate modeling of future ranges for vertebrates in California's Sierra Nevada. The approach also offers a new method for use in assessment of vertebrate vulnerability in other mountain regions, and can be an important component of assessing their vulnerability to climate change.

Savage, J., and M. Vellend. 2015. **Elevational shifts, biotic homogenization and time lags in vegetation change during 40 years of climate warming.** Ecography 38:546-555.

Abstract. Many species show evidence of climate-driven distribution shifts towards higher elevations, but given the tremendous variation among species and regions, we lack an understanding of the community-level consequences of such shifts. Here we test for signatures of climate warming impacts using a repeat survey of semi-

permanent vegetation plots in 1970 and 2012 in a montane protected area in southern Québec, Canada, where daily maximum and minimum temperatures have increased by ~1.6°C and ~2.5°C over the same time period. As predicted, the abundance-weighted mean elevations of species distributions increased significantly over time (9 m/decade). A community temperature index (CTI) was calculated as the abundance-weighted mean of the median temperature across occurrences within each species geographic range in eastern North America. CTI did not vary significantly over time, although the raw magnitude of change (+ 0.2°C) matched the expectation based on the upward shift in distributions of 9 m/decade. Species composition of high elevation sites converged over time toward that observed at low elevation, although compositional changes at low elevation sites were more modest. As a consequence, the results of a multivariate analysis showed a decline in among-plot compositional variability (i.e. beta diversity) over time, thus providing some of the first empirical evidence linking climate warming with biotic homogenization. Finally, plot-scale species richness showed a marked increase of ~25% on average. Overall, elevational distribution shifts, biodiversity change, and biotic homogenization over the past four decades have been consistent with predictions based on climate warming, although the rate of change has been relatively slow, suggesting substantial time lags in biotic responses to climate change.

Serra-Diaz, J., R. Scheller, A. Syphard, and J. Franklin. 2015. **Disturbance and climate microrefugia mediate tree range shifts during climate change.** Landscape Ecology 30:1039-1053.

Abstract. Context. Many tree species will shift their distribution as the climate continues to change. To assess species' range changes, modeling efforts often rely on climatic predictors, sometimes incorporating biotic interactions (e.g. competition or facilitation), but without integrating topographic complexity or the dynamics of disturbance and forest succession.

Objectives. We investigated the role of 'safe islands' of establishment ("microrefugia") in conjunction with disturbance and succession, on mediating range shifts.

Methods. We simulated eight tree species and multiple disturbances across an artificial landscape designed to highlight variation in topographic complexity. Specifically, we simulated spatially explicit successional changes for a 100-year period of climate warming under different scenarios of disturbance and climate microrefugia.

Results. Disturbance regimes play a major role in mediating species range changes. The effects of disturbance range from expediting range contractions for some species to facilitating colonization of new ranges for others. Microrefugia generally had a significant but smaller effect on range changes. The existence of microrefugia could enhance range persistence but implies increased environmental heterogeneity, thereby hampering migration under some disturbance regimes and for species with low dispersal capabilities. Species that gained suitable habitat due to climate change largely depended on the interaction between species life history traits, environmental heterogeneity and disturbance regimes to expand their ranges.

Conclusions. Disturbance and microrefugia play a key role in determining forest range shifts during climate change. The study highlights the urgent need of including non-deterministic successional pathways into climate change projections of species distributions.

Šímová, I., C. Violle, N. J. B. Kraft, D. Storch, J.-C. Svenning, B. Boyle, J. C. Donoghue, P. Jørgensen, B. J. McGill, N. Morueta-Holme, W. H. Piel, R. K. Peet, J. Regetz, M. Schildhauer, N. Spencer, B. Thiers, S. Wiser, and B. J. Enquist. 2015. **Shifts in trait means and variances in North American tree assemblages: species richness patterns are loosely related to the functional space.** Ecography 38:649-658.

Abstract. One of the key hypothesized drivers of gradients in species richness is environmental filtering, where environmental stress limits which species from a larger species pool gain membership in a local community owing to their traits. Whereas most studies focus on small-scale variation in functional traits along environmental gradient, the effect of large-scale environmental filtering is less well understood. Furthermore, it has been rarely tested whether the factors that constrain the niche space limit the total number of coexisting species. We assessed the role of environmental filtering in shaping tree assemblages across North America north of Mexico by testing the hypothesis that colder, drier, or seasonal environments (stressful conditions for most plants) constrain tree trait diversity and thereby limit species richness. We assessed geographic patterns in trait filtering and their relationships to species richness pattern using a comprehensive set of tree range maps. We focused on four key plant functional traits reflecting major life history axes (maximum height, specific leaf area, seed mass, and wood density) and four climatic variables (annual mean and seasonality of temperature and precipitation). We tested for significant spatial shifts in trait means and

variances using a null model approach. While we found significant shifts in mean species' trait values at most grid cells, trait variances at most grid cells did not deviate from the null expectation. Measures of environmental harshness (cold, dry, seasonal climates) and lower species richness were weakly associated with a reduction in variance of seed mass and specific leaf area. The pattern in variance of height and wood density was, however, opposite. These findings do not support the hypothesis that more stressful conditions universally limit species and trait diversity in North America. Environmental filtering does, however, structure assemblage composition, by selecting for certain optimum trait values under a given set of conditions.

Forest Vegetation

Allen, C. D., D. D. Breshears, and N. G. McDowell. 2015. **On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene.** Ecosphere 6:art129.

Abstract. Patterns, mechanisms, projections, and consequences of tree mortality and associated broad-scale forest die-off due to drought accompanied by warmer temperatures—"hotter drought", an emerging characteristic of the Anthropocene—are the focus of rapidly expanding literature. Despite recent observational, experimental, and modeling studies suggesting increased vulnerability of trees to hotter drought and associated pests and pathogens, substantial debate remains among research, management and policy-making communities regarding future tree mortality risks. We summarize key mortality-relevant findings, differentiating between those implying lesser versus greater levels of vulnerability. Evidence suggesting lesser vulnerability includes forest benefits of elevated [CO_2] and increased water-use efficiency; observed and modeled increases in forest growth and canopy greening; widespread increases in woody-plant biomass, density, and extent; compensatory physiological, morphological, and genetic mechanisms; dampening ecological feedbacks; and potential mitigation by forest management. In contrast, recent studies document more rapid mortality under hotter drought due to negative tree physiological responses and accelerated biotic attacks. Additional evidence suggesting greater vulnerability includes rising background mortality rates; projected increases in drought frequency, intensity, and duration; limitations of vegetation models such as inadequately represented mortality processes; warming feedbacks from die-off; and

wildfire synergies. Grouping these findings we identify ten contrasting perspectives that shape the vulnerability debate but have not been discussed collectively. We also present a set of global vulnerability drivers that are known with high confidence: (1) droughts eventually occur everywhere; (2) warming produces hotter droughts; (3) atmospheric moisture demand increases nonlinearly with temperature during drought; (4) mortality can occur faster in hotter drought, consistent with fundamental physiology; (5) shorter droughts occur more frequently than longer droughts and can become lethal under warming, increasing the frequency of lethal drought nonlinearly; and (6) mortality happens rapidly relative to growth intervals needed for forest recovery. These high-confidence drivers, in concert with research supporting greater vulnerability perspectives, support an overall viewpoint of greater forest vulnerability globally. We surmise that mortality vulnerability is being discounted in part due to difficulties in predicting threshold responses to extreme climate events. Given the profound ecological and societal implications of underestimating global vulnerability to hotter drought, we highlight urgent challenges for research, management, and policy-making communities.

Anderegg, W. R. L., C. Schwalm, F. Biondi, J. J. Camarero, G. Koch, M. Litvak, K. Ogle, J. D. Shaw, E. Shevliakova, A. P. Williams, A. Wolf, E. Ziaco, and S. Pacala. 2015. **Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models.** Science 349:528-532.

Abstract. The impacts of climate extremes on terrestrial ecosystems are poorly understood but important for predicting carbon cycle feedbacks to climate change. Coupled climate–carbon cycle models typically assume that vegetation recovery from extreme drought is immediate and complete, which conflicts with the understanding of basic plant physiology. We examined the recovery of stem growth in trees after severe drought at 1338 forest sites across the globe, comprising 49,339 site-years, and compared the results with simulated recovery in climate-vegetation models. We found pervasive and substantial “legacy effects” of reduced growth and incomplete recovery for 1 to 4 years after severe drought. Legacy effects were most prevalent in dry ecosystems, among Pinaceae, and among species with low hydraulic safety margins. In contrast, limited or no legacy effects after drought were simulated by current climate-vegetation models. Our results highlight hysteresis in ecosystem-level carbon cycling and delayed recovery from climate extremes.

Dobrowski, S. Z., A. K. Swanson, J. T. Abatzoglou, Z. A. Holden, H. D. Safford, M. K. Schwartz, and D. G. Gavin. 2015. **Forest structure and species traits mediate projected recruitment declines in western US tree species.** Global Ecology and Biogeography 24:917-927.

Abstract. Aim. Determine if differences in the climatic niche between conspecific adult and juvenile trees of the western Unites States vary by species traits and to assess if forest canopies moderate the sensitivity of juvenile trees to climatic variation.

Location. The western United States.

Methods. Using data from the USDA Forest Inventory and Analysis programme, we compare the distribution of conspecific adult and juvenile trees for 62 western US tree species. We relate demographic niche differences to species traits including shade and drought tolerance. We model recruitment under projected climate change using generalized linear mixed models, probabilistic uncertainty accounting, forest structural data and projected changes in the climatic water balance.

Results. On average juveniles of western US tree species occupy a climatic subset of their conspecific adults. Demographic niche differences increase as species shade and drought tolerance increase and are greatest at climatic range margins, indicating the potential for range contractions. Models calibrated solely with climate data project recruitment declines for 2080 that are 47% larger on average than models that also account for forest structure.

Main conclusions. Climate change-driven declines in recruitment in western US tree species may be partly offset by the moderating effect of forest canopies. The importance of this stabilizing process will depend on whether a given site is disturbed and the traits of resident species, including their ability to utilize sites that have buffered microclimates. Conversely, our results suggest that broad-scale disturbances which result in the loss of forest canopy will amplify the effects of climate change on tree recruitment.

Dugan, A. J., and W. L. Baker. 2015. **Sequentially contingent fires, droughts and pluvials structured a historical dry forest landscape and suggest future contingencies.** Journal of Vegetation Science 26:697-710.

Abstract. Questions. Dry forests throughout the world were historically influenced by fires and climatic events, evidenced by tree recruitment pulses in forest age structures, but did these influences act randomly or were recruitment pulses contingent on the type, magnitude, order and timing of events? If recruitment was random or contingent, what are the implications for future forests?

Location. Unlogged, old-growth ponderosa pine landscape in Grand Canyon National Park, Arizona, US.

Methods. We spatially reconstructed and compared tree recruitment pulses evident in forest age structures within plots with tree ring reconstructions of pluvials, droughts, fires and fire quiescence (longer fire-free periods). We used chi-square analysis to test for sequential contingency of combinations and permutations of pulse influences.

Results. Of 20 recruitment pulses, 17 were influenced to some extent by fire quiescence, 13 by fires and droughts each, and 11 by pluvials. Prevalence of pulses across the landscape did not correspond to the pronounced spatial variability in fire rotation. Analysis of combinations and permutations of these influences showed that potentially mortality-inducing influences of fire and drought likely initiated pulses, whereas pluvials and quiescence, which enhance recruitment conditions, sustained 75% of pulses.

Conclusions. Successful tree recruitment pulses in dry forests historically were sequentially contingent on mortality-inducing influences, followed by recruitment-enhancing conditions. The impacts of climate change projections, including prolonged droughts and intense fires, on dry forests may depend on the order, timing and magnitude of influences.

Lankau, R. A., K. Zhu, and A. Ordonez. 2015. **Mycorrhizal strategies of tree species correlate with trailing range edge responses to current and past climate change.** Ecology 96:1451-1458.

Abstract. As climates shift in space, tree species ranges are predicted to shift as well. While range shifts due to climate change have been typically modeled based on abiotic factors alone, interactions among species in diverse communities may alter these range dynamics by inhibiting or enhancing the establishment of propagules along the

leading edge, or by increasing or decreasing tolerance to novel climates at the trailing edge. Here, we investigated how the rate of expansion at leading range margins, and contraction at trailing range margins of temperate tree species in response to both past and current climate change related to an important species interaction: whether temperate tree species associate with arbuscular (AM) or ectomycorrhizal (EM) fungal symbionts. Mycorrhizal symbioses can mediate plant stress tolerance, and lack of EM fungal mutualists has been linked to establishment failures of EM tree species in new ranges. We found no difference in rates of leading edge expansion between the two guilds. However, EM tree taxa showed reduced contraction at their trailing edge compared to AM taxa in response to both past and current climate change. Since the mycorrhizal guild of the dominant trees may affect ecosystem properties, differential range dynamics between these functional groups of trees may have consequences for the functioning of future forests.

Marcinkowski, K., D. L. Peterson, and G. J. Ettl. 2015. **Nonstationary temporal response of mountain hemlock growth to climatic variability in the North Cascade Range, Washington, USA.** Canadian Journal of Forest Research 45:676-688.

Abstract. A stationary response of tree radial growth to climatic variables is assumed as a basis for climatic reconstructions and future growth projections in response to climate change. Mountain hemlock (*Tsuga mertensiana* (Bong.) Carrière) trees on the western slopes of the North Cascade Range (Washington, USA) were examined for stability in growth response to climatic influences at a small spatial scale. Moving correlation functions demonstrate that climate–growth interactions are nonstationary over time, alternating between periods of significant and nonsignificant responses. Correlations between growth and winter precipitation have weakened, becoming statistically insignificant in the last decade, but correlations with spring temperature and previous-year summer temperature have strengthened, becoming statistically significant. The Pacific Decadal Oscillation influences patterns in climate–growth correlations but does not seem to account for the most recent changes in correlation strength. At an interannual scale, growth differs between El Niño Southern Oscillation phases, specifically between El Niño and La Niña years and between La Niña and neutral phase years. The variability in growth response to climate at interannual and interdecadal time frames, especially with the climate changes emerging in recent

decades, will challenge the reliability and accuracy of reconstruction and predictive models

McDowell, N. G., and C. D. Allen. 2015. **Darcy's law predicts widespread forest mortality under climate warming.** Nature Climate Change 5:669-672.

Abstract. Drought and heat-induced tree mortality is accelerating in many forest biomes as a consequence of a warming climate, resulting in a threat to global forests unlike any in recorded. Forests store the majority of terrestrial carbon, thus their loss may have significant and sustained impacts on the global carbon cycle. We use a hydraulic corollary to Darcy’s law, a core principle of vascular plant physiology, to predict characteristics of plants that will survive and die during drought under warmer future climates. Plants that are tall with isohydric stomatal regulation, low hydraulic conductance, and high leaf area are most likely to die from future drought stress. Thus, tall trees of old-growth forests are at the greatest risk of loss, which has ominous implications for terrestrial carbon storage. This application of Darcy’s law indicates today’s forests generally should be replaced by shorter and more xeric plants, owing to future warmer droughts and associated wildfires and pest attacks. The Darcy’s corollary also provides a simple, robust framework for informing forest management interventions needed to promote the survival of current forests. Given the robustness of Darcy’s law for predictions of vascular plant function, we conclude with high certainty that today’s forests are going to be subject to continued increases in mortality rates that will result in substantial reorganization of their structure and carbon storage.

Pangle, R., K. Kavanagh, and R. Duursma. 2015. **Decline in canopy gas exchange with increasing tree height, atmospheric evaporative demand, and seasonal drought in co-occurring inland Pacific Northwest conifer species.** Canadian Journal of Forest Research 45:1086-1101.

Abstract. Interspecific variation in stomatal conductance (G_S) and transpiration (E_L) has been documented in stands of co-occurring species, and this variation has been observed to differ with tree size and canopy height increase. In this study, we present data that examine fluctuations in canopy gas exchange across co-occurring species and varying canopy heights for three montane forest chronosequences located in an inland Pacific Northwest mixed-conifer forest. With the exception of Douglas-fir (*Pseudotsuga menziesii* var.

glauca (Beissn.) Franco), we observed consistent declines in canopy E_L and G_S with increasing height for the majority of species examined in our 2-year study. Along with declines in canopy G_S, we observed decreases in leaf-specific hydraulic conductance (K_L) across species as canopy height increased. Seasonally, we observed declines in canopy G_S during warmer and dryer summer months of both years. These decreases in G_S were significant (up to 50%) and suggest that carbon assimilation in trees was limited during dryer months due to a combination of high evaporative demand and reduced soil H_2O availability. Such reductions in G_S during periods of increased plant water stress suggest that forest productivity in the inland Pacific Northwest may be impacted negatively if future climate predictions of increasing growing-season water stress are realized.

Sample, V. Alaric; Bixler, R. Patrick, eds. 2014. **Forest conservation and management in the Anthropocene: Conference proceedings. Proceedings.** RMRS-P-71. Fort Collins, CO: US Department of Agriculture, Forest Service. Rocky Mountain Research Station. 494 p.

Abstract. Climate change is but one aspect of the Anthropocene, a new epoch in which the effects of human activities have become the predominant force in the global biosphere. More than just an overlay on the traditional concerns of sustainable natural resource management, the uncertainties associated with these effects are creating a “no-analog future” in which much of the existing science relating to the functioning and response of forest ecosystems - which serves as the fundamental basis for current forest management practices and policies - must be reconsidered. In these collected papers, leading scientists, resource managers and policy specialists explore the implications of climate change and other manifestations of the Anthropocene on the management of wildlife habitat, biodiversity, water, and other resources, with particular attention to the effects of wildfire. Recommendations include the need for a supporting institutional, legal, and policy framework that is not just different but more dynamic, to facilitate resource management adaptation and preparedness in a period of accelerating environmental change. Available at http://www.fs.fed.us/rm/pubs/rmrs_p071.html.

Rangeland Vegetation

Briske, D. D., L. A. Joyce, H. W. Polley, J. R. Brown, K. Wolter, J. A. Morgan, B. A. McCarl, and D. W. Bailey. 2015. **Climate-change adaptation on rangelands: linking regional exposure with diverse adaptive capacity.** Frontiers in Ecology and the Environment 13:249-256.

Abstract. The ecological consequences of climate change are predicted to vary greatly throughout US rangelands. Projections show warming and drying in the southern Great Plains and the Southwest, warmer and drier summers with reduced winter snowpack in the Northwest, and warmer and wetter conditions in the northern Great Plains. Primarily through their combined effects on soil water availability, these climatic changes will modify plant production and community composition, which will, in turn, affect the livelihoods of humans who rely upon livestock grazing. The ability of rangeland managers to assess risk and prepare for climate change varies greatly and reflects their different adaptive capacities. Geographically specific exposure to climate change and a diverse adaptive capacity to counteract these changes will require development of varied adaptation strategies that can accommodate the various needs and abilities of livestock managers.

Harrison, S. P., E. S. Gornish, and S. Copeland. 2015. **Climate-driven diversity loss in a grassland community.** Proceedings of the National Academy of Sciences 112:8672-8677.

Abstract. Local ecological communities represent the scale at which species coexist and share resources, and at which diversity has been experimentally shown to underlie stability, productivity, invasion resistance, and other desirable community properties. Globally, community diversity shows a mixture of increases and decreases over recent decades, and these changes have relatively seldom been linked to climatic trends. In a heterogeneous California grassland, we documented declining plant diversity from 2000 to 2014 at both the local community (5 m^2) and landscape (27 km^2) scales, across multiple functional groups and soil environments. Communities became particularly poorer in native annual forbs, which are present as small seedlings in midwinter; within native annual forbs, community composition changed toward lower representation of species with a trait indicating drought intolerance (high specific leaf area). Time series models linked diversity decline to the significant decrease in midwinter precipitation. Livestock grazing history, fire, succession, N

deposition, and increases in exotic species could be ruled out as contributing causes. This finding is among the first demonstrations to our knowledge of climate-driven directional loss of species diversity in ecological communities in a natural (nonexperimental) setting. Such diversity losses, which may also foreshadow larger-scale extinctions, may be especially likely in semiarid regions that are undergoing climatic trends toward higher aridity and lower productivity.

Loik, M. E., A. B. Griffith, H. Alpert, A. L. Concilio, C. E. Wade, and S. J. Martinson. 2015. **Impact of intra- versus inter-annual snow depth variation on water relations and photosynthesis for two Great Basin Desert shrubs.** Oecologia 178:403-414.

Abstract. Snowfall provides the majority of soil water in certain ecosystems of North America. We tested the hypothesis that snow depth variation affects soil water content, which in turn drives water potential (Ψ) and photosynthesis, over 10 years for two widespread shrubs of the western USA. Stem Ψ (Ψ stem) and photosynthetic gas exchange [stomatal conductance to water vapor (g_s), and CO2 assimilation (A)] were measured in mid-June each year from 2004 to 2013 for *Artemisia tridentata* var. *vaseyana* (Asteraceae) and *Purshia tridentata* (Rosaceae). Snow fences were used to create increased or decreased snow depth plots. Snow depth on +snow plots was about twice that of ambient plots in most years, and 20 % lower on −snow plots, consistent with several down-scaled climate model projections. Maximal soil water content at 40- and 100-cm depths was correlated with February snow depth. For both species, multivariate ANOVA (MANOVA) showed that Ψ stem, g_s, and A were significantly affected by intra-annual variation in snow depth. Within years, MANOVA showed that only A was significantly affected by spatial snow depth treatments for *A. tridentata*, and Ψ stem was significantly affected by snow depth for *P. tridentata*. Results show that stem water relations and photosynthetic gas exchange for these two cold desert shrub species in mid-June were more affected by inter-annual variation in snow depth by comparison to within-year spatial variation in snow depth. The results highlight the potential importance of changes in inter-annual variation in snowfall for future shrub photosynthesis in the western Great Basin Desert.

Nippert, J. B., and R. M. Holdo. 2015. **Challenging the maximum rooting depth paradigm in grasslands and savannas.** Functional Ecology 29:739-745.

Abstract. For many grassland and savanna ecosystems, water limitation is a key regulator of individual plant, community and ecosystem processes. Maximum rooting depth is commonly used to characterize the susceptibility of plant species to drought. This rests on the assumption that deep-rooted plant species would have a greater total volume of soil water to exploit and should be less susceptible to episodic changes in water availability.

Independent of maximum rooting depth, rooting strategies based on differences in biomass allocation with depth, uptake plasticity in relation to water availability and variation in water transport capability may all influence growth responses and susceptibility to drought. Many examples from grasslands and savannas reflect these rooting strategies among coexisting grass, forb and woody species.

Here, we use a dynamic model of plant water uptake and growth to show how changes in root distribution, functional plasticity and root hydraulic conductivity have the potential to influence aboveground biomass and competitive outcomes, even when maximum rooting depth remains constant. We also show theoretically that shifts in root distribution to surface soils without changes in maximum depth can potentially outweigh the benefits of increased maximum rooting depth.

Combining our current reliance on biogeographic descriptions of maximum rooting depth with insights about other, more subtle aspects of root structure and function are likely to improve our understanding of ecosystem responses to dynamic water limitation.

Riparian Vegetation

Garssen, A. G., A. Baattrup-Pedersen, L. A. C. J. Voesenek, J. T. A. Verhoeven, and M. B. Soons. 2015. **Riparian plant community responses to increased flooding: a meta-analysis.** Global Change Biology 21:2881-2890.

Abstract. A future higher risk of severe flooding of streams and rivers has been projected to change riparian plant community composition and species richness, but the extent and direction of the expected change remain uncertain. We conducted a meta-analysis to synthesize globally available experimental evidence and assess the effects of increased flooding on (1) riparian adult plant and seedling survival, (2)

riparian plant biomass and (3) riparian plant species composition and richness. We evaluated which plant traits are of key importance for the response of riparian plant species to flooding. We identified and analysed 53 papers from ISI Web of Knowledge which presented quantitative experimental results on flooding treatments and corresponding control situations. Our meta-analysis demonstrated how longer duration of flooding, greater depth of flooding and, particularly, their combination reduce seedling survival of most riparian species. Plant height above water level, ability to elongate shoots and plasticity in root porosity were decisive for adult plant survival and growth during longer periods of flooding. Both ‘quiescence’ and ‘escape’ proved to be successful strategies promoting riparian plant survival, which was reflected in the wide variation in survival (full range between 0 and 100%) under fully submerged conditions, while plants that protrude above the water level (>20 cm) almost all survive. Our survey confirmed that the projected increase in the duration and depth of flooding periods is sufficient to result in species shifts. These shifts may lead to increased or decreased riparian species richness depending on the nutrient, climatic and hydrological status of the catchment. Species richness was generally reduced at flooded sites in nutrient-rich catchments and sites that previously experienced relatively stable hydrographs (e.g. rain-fed lowland streams). Species richness usually increased at sites in desert and semi-arid climate regions (e.g. intermittent streams).

Fish and Wildlife

Buckley, L. B., J. C. Ehrenberger, and M. J. Angilletta. 2015. **Thermoregulatory behaviour limits local adaptation of thermal niches and confers sensitivity to climate change.** Functional Ecology 29:1038-1047.

Abstract. Thermoregulation buffers environmental variation, which enables a species to persist during climate change but ultimately hinders adaptation of thermal tolerance by weakening selective pressure.

We used a model of optimal thermal physiology to demonstrate how thermoregulatory behaviour limits local adaptation of thermal physiology in a widespread group of lizards, the *Sceloporus undulatus* complex.

Empirical data for seven populations demonstrates conservatism of thermal tolerance, consistent with the model's prediction in the case of effective thermoregulation. In an eighth population, from a region where thermoregulation should be less effective, we observed greater heat tolerance and poorer cold tolerance, as predicted by our model.

Biophysical modelling indicates that lizards can avoid heat stress through thermoregulation in the coming decades but will ultimately experience an abrupt decline in the effectiveness of thermoregulation. In this scenario, thermoregulators will suffer a greater loss of performance in future climates than thermoconformers will, unless heat tolerance can evolve in a few generations.

Our analyses raises a concern that behavioural plasticity, while beneficial in the short term, will ultimately limit the physiological adaptation required to endure a warming climate.

Isaak, D. J., M. K. Young, D. E. Nagel, D. L. Horan, and M. C. Groce. 2015. **The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century.** Global Change Biology 21:2540-2553.

Abstract. The distribution and future fate of ectothermic organisms in a warming world will be dictated by thermalscapes across landscapes. That is particularly true for stream fishes and cold-water species like trout, salmon, and char that are already constrained to high elevations and latitudes. The extreme climates in those environments also preclude invasions by most non-native species, so identifying especially cold habitats capable of absorbing future climate change while still supporting native populations would highlight important refugia. By coupling crowd-sourced biological datasets with high-resolution stream temperature scenarios, we delineate network refugia across >250 000 stream km in the Northern Rocky Mountains for two native salmonids—bull trout (BT) and cutthroat trout (CT). Under both moderate and extreme climate change scenarios, refugia with high probabilities of trout population occupancy (>0.9) were predicted to exist (33–68 BT refugia; 917–1425 CT refugia). Most refugia are on public lands (>90%) where few currently have protected status in National Parks or Wilderness Areas (<15%). Forecasts of refuge locations could enable protection of key watersheds and provide a foundation for climate smart planning of conservation networks. Using cold water as a ‘climate shield’ is generalizable to other species and geographic areas because it has a strong physiological basis, relies on nationally available geospatial data, and mines existing biological datasets. Importantly, the approach creates a framework to integrate

data contributed by many individuals and resource agencies, and a process that strengthens the collaborative and social networks needed to preserve many cold-water fish populations through the 21st century.

Kopf, R. K., C. M. Finlayson, P. Humphries, N. C. Sims, and S. Hladyz. 2015. **Anthropocene baselines: assessing change and managing biodiversity in human-dominated aquatic ecosystems.** BioScience 65:798-811.

Abstract. Global ecosystems have shifted from historical conditions, but it is unclear from what baselines change should be assessed. Scientists and managers have increasingly accepted the impossibility of returning ecosystems to a “pristine” state; however, historical conditions remain the cornerstone for restoration and management. We explore the rationale behind the application of historical baselines to ecosystem management and propose Anthropocene baselines as a concept to provide an improved basis for the management of human-dominated ecosystems. The Anthropocene baselines concept emphasizes the conservation value of the remnants of historical ecosystems but confronts the reality that many ecosystems cannot—or will not—be restored to historical ranges of variability. In order to prevent further unwanted changes to biodiversity and ecosystem services, we suggest that the management of human-dominated ecosystems must move beyond historical constraints toward new points of reference dictated by social–ecological sustainability.

Kovach, R. P., C. C. Muhlfeld, A. A. Wade, B. K. Hand, D. C. Whited, P. W. DeHaan, R. Al-Chokhachy, and G. Luikart. 2015. **Genetic diversity is related to climatic variation and vulnerability in threatened bull trout.** Global Change Biology 21:2510-2524.

Abstract. Understanding how climatic variation influences ecological and evolutionary processes is crucial for informed conservation decision-making. Nevertheless, few studies have measured how climatic variation influences genetic diversity within populations or how genetic diversity is distributed across space relative to future climatic stress. Here, we tested whether patterns of genetic diversity (allelic richness) were related to climatic variation and habitat features in 130 bull trout (*Salvelinus confluentus*) populations from 24 watersheds (i.e., ~4–7th order river subbasins) across the Columbia River Basin, USA. We then determined whether bull trout genetic diversity was related to climate vulnerability at the watershed scale, which we quantified on the basis of exposure to future climatic conditions (projected scenarios for the 2040s) and existing habitat complexity. We found a strong gradient in genetic diversity in bull trout populations across the Columbia River Basin, where populations located in the most upstream headwater areas had the greatest genetic diversity. After accounting for spatial patterns with linear mixed models, allelic richness in bull trout populations was positively related to habitat patch size and complexity, and negatively related to maximum summer temperature and the frequency of winter flooding. These relationships strongly suggest that climatic variation influences evolutionary processes in this threatened species and that genetic diversity will likely decrease due to future climate change. Vulnerability at a watershed scale was negatively correlated with average genetic diversity ($r = -0.77$; $P < 0.001$); watersheds containing populations with lower average genetic diversity generally had the lowest habitat complexity, warmest stream temperatures, and greatest frequency of winter flooding. Together, these findings have important conservation implications for bull trout and other imperiled species. Genetic diversity is already depressed where climatic vulnerability is highest; it will likely erode further in the very places where diversity may be most needed for future persistence.

Lane, D., R. Jones, D. Mills, C. Wobus, R. Ready, R. Buddemeier, E. English, J. Martinich, K. Shouse, and H. Hosterman. 2015. **Climate change impacts on freshwater fish, coral reefs, and related ecosystem services in the United States.** Climatic Change 131:143-157.

Abstract. We analyzed the potential physical and economic impacts of climate change on freshwater fisheries and coral reefs in the United States, examining a reference case and two policy scenarios that limit global greenhouse gas (GHG) emissions. We modeled shifts in suitable habitat for three freshwater fish guilds and changes in coral reef cover for three regions. We estimated resulting economic impacts from projected changes in recreational fishing and changes in recreational use of coral reefs. In general, coldwater fisheries are projected to be replaced by less desirable fisheries over the 21st century, but these impacts are reduced under the GHG mitigation scenarios. Similarly, coral cover is projected to decline over the 21st century primarily due to multiple bleaching events, but the GHG mitigation scenarios delay these declines in Hawaii (but not in South Florida or Puerto Rico). Using a benefit-transfer approach, we estimated that global policies limiting GHG emissions would provide economic benefits in the range

of $10–28 billion over the 21st century through maintaining higher values for recreational services for all freshwater fisheries and coral reefs, compared to the reference scenario. These economic values are a subset of the total economic and societal benefits associated with avoiding projected future declines in freshwater fisheries and coral reef cover due to unmitigated climate change.

Levy, O., L. B. Buckley, T. H. Keitt, C. D. Smith, K. O. Boateng, D. S. Kumar, and M. J. Angilletta. 2015. **Resolving the life cycle alters expected impacts of climate change.** Proceedings of the Royal Society B: Biological Sciences 282:20150837.

Abstract. Recent models predict contrasting impacts of climate change on tropical and temperate species, but these models ignore how environmental stress and organismal tolerance change during the life cycle. For example, geographical ranges and extinction risks have been inferred from thermal constraints on activity during the adult stage. Yet, most animals pass through a sessile embryonic stage before reaching adulthood, making them more susceptible to warming climates than current models would suggest. By projecting microclimates at high spatio-temporal resolution and measuring thermal tolerances of embryos, we developed a life cycle model of population dynamics for North American lizards. Our analyses show that previous models dramatically underestimate the demographic impacts of climate change. A predicted loss of fitness in 2% of the USA by 2100 became 35% when considering embryonic performance in response to hourly fluctuations in soil temperature. Most lethal events would have been overlooked if we had ignored thermal stress during embryonic development or had averaged temperatures over time. Therefore, accurate forecasts require detailed knowledge of environmental conditions and thermal tolerances throughout the life cycle.

Slavenko, A., and S. Meiri. 2015. **Mean body sizes of amphibian species are poorly predicted by climate.** Journal of Biogeography 42:1246-1254.

Abstract. Aim. Climate is thought to exert a strong influence on animal body sizes. We examined the relationship between amphibian body size and several climatic variables to discern which climatic variables, if any, affect amphibian size evolution.

Location. Europe and North America.

Methods. We assembled a dataset of mean sizes of 356 (out of 360) amphibian species in Europe, the USA and Canada, and tested how they are related to temperature, precipitation, primary productivity and seasonality. First, we examined the body size distributions of all the species inhabiting equal-area grid cells (of 96.3 km × 96.3 km) using randomizations to account for the effects of species richness. Second, we examined the relationship between mean species body size and the environmental predictors across their ranges accounting for phylogenetic effects.

Results. The observed amphibian body size distributions were mostly statistically indistinguishable from distributions generated by random assignment of species to cells. Median sizes in grid cells were negatively correlated with temperature in anurans and positively in urodeles. The phylogenetic analysis revealed opposite trends in relation to temperature. In both clades most climatic variables were not associated with size and the few significant relationships were very weak.

Main conclusions. Spatial patterns in amphibian body size probably reflect diversity gradients, and relationships with climate could result from spurious effects of richness patterns. The large explanatory power of richness in the grid-cell analysis, and the small explanatory power of climate in the interspecific analysis, signify that climate per se has little effect on amphibian body sizes.

Terry, R. C., and R. J. Rowe. 2015. **Energy flow and functional compensation in Great Basin small mammals under natural and anthropogenic environmental change.** Proceedings of the National Academy of Sciences 112:9656-9661.

Abstract. Research on the ecological impacts of environmental change has primarily focused at the species level, leaving the responses of ecosystem-level properties like energy flow poorly understood. This is especially so over millennial timescales inaccessible to direct observation. Here we examine how energy flow within a Great Basin small mammal community responded to climate-driven environmental change during the past 12,800 y, and use this baseline to evaluate responses observed during the past century. Our analyses reveal marked stability in energy flow during rapid climatic warming at the terminal Pleistocene despite dramatic turnover in the distribution of mammalian body sizes and habitat-associated functional groups. Functional group turnover was strongly correlated with climate-driven changes in regional vegetation, with climate and vegetation change

preceding energetic shifts in the small mammal community. In contrast, the past century has witnessed a substantial reduction in energy flow caused by an increase in energetic dominance of small-bodied species with an affinity for closed grass habitats. This suggests that modern changes in land cover caused by anthropogenic activities—particularly the spread of nonnative annual grasslands—has led to a breakdown in the compensatory dynamics of energy flow. Human activities are thus modifying the small mammal community in ways that differ from climate-driven expectations, resulting in an energetically novel ecosystem. Our study illustrates the need to integrate across ecological and temporal scales to provide robust insights for long-term conservation and management.

Ward, E. J., J. H. Anderson, T. J. Beechie, G. R. Pess, and M. J. Ford. 2015. **Increasing hydrologic variability threatens depleted anadromous fish populations.** Global Change Biology 21:2500-2509.

Abstract. Predicting effects of climate change on species and ecosystems depend on understanding responses to shifts in means (such as trends in global temperatures), but also shifts in climate variability. To evaluate potential responses of anadromous fish populations to an increasingly variable environment, we performed a hierarchical analysis of 21 Chinook salmon populations from the Pacific Northwest, examining support for changes in river flows and flow variability on population growth. More than half of the rivers analyzed have already experienced significant increases in flow variability over the last 60 years, and this study shows that this increase in variability in freshwater flows has a more negative effect than any other climate signal included in our model. Climate change models predict that this region will experience warmer winters and more variable flows, which may limit the ability of these populations to recover.

Invertebrates

Buckley, L. B., C. R. Nufio, E. M. Kirk, and J. G. Kingsolver. 2015. **Elevational differences in developmental plasticity determine phenological responses of grasshoppers to recent climate warming.** Proceedings of the Royal Society B: Biological Sciences 282: 20150441

Abstract. Annual species may increase reproduction by increasing adult body size through extended development, but risk being unable to complete development in seasonally limited environments. Synthetic reviews indicate that most, but not all, species have responded to recent climate warming by advancing the seasonal timing of adult emergence or reproduction. Here, we show that 50 years of climate change have delayed development in high-elevation, season-limited grasshopper populations, but advanced development in populations at lower elevations. Developmental delays are most pronounced for early-season species, which might benefit most from delaying development when released from seasonal time constraints. Rearing experiments confirm that population, elevation and temperature interact to determine development time. Population differences in developmental plasticity may account for variability in phenological shifts among adults. An integrated consideration of the full life cycle that considers local adaptation and plasticity may be essential for understanding and predicting responses to climate change.

Kerr, J. T., A. Pindar, P. Galpern, L. Packer, S. G. Potts, S. M. Roberts, P. Rasmont, O. Schweiger, S. R. Colla, L. L. Richardson, D. L. Wagner, L. F. Gall, D. S. Sikes, and A. Pantoja. 2015. **Climate change impacts on bumblebees converge across continents.** Science 349:177-180.

Abstract. For many species, geographical ranges are expanding toward the poles in response to climate change, while remaining stable along range edges nearest the equator. Using long-term observations across Europe and North America over 110 years, we tested for climate change–related range shifts in bumblebee species across the full extents of their latitudinal and thermal limits and movements along elevation gradients. We found cross-continentally consistent trends in failures to track warming through time at species' northern range limits, range losses from southern range limits, and shifts to higher elevations among southern species. These effects are independent of changing land uses or pesticide applications and underscore the need

to test for climate impacts at both leading and trailing latitudinal and thermal limits for species.

Kollberg, I., H. Bylund, T. Jonsson, A. Schmidt, J. Gershenzon, and C. Björkman. 2015. **Temperature affects insect outbreak risk through tritrophic interactions mediated by plant secondary compounds.** Ecosphere 6:art102.

Abstract. Global warming may affect population dynamics of herbivorous insects since the relative impact of bottom-up and top-down processes on herbivore survival is likely to be influenced by temperature. However, little is known about the mechanisms by which warming could affect regulation of populations, particularly when indirect effects across trophic levels are involved. We quantified larval survival of the needle-feeding European pine sawfly, *Neodiprion sertifer*, either protected from (caged) or exposed to natural enemies at three geographically separated localities in Sweden. The study shows that larval survival is affected by temperature but the direction of the effect is influenced by plant secondary compounds (diterpenes). The results suggest that survival of exposed larvae feeding on needles with high diterpene concentrations will decrease with increasing temperature, while larval survival on low diterpene concentration is less predictable with either no change or an increase with temperature. This food quality dependent response to temperature is probably due to diterpenes having a double-sided effect on larvae; both a negative toxic effect and a positive anti-predator defense effect. Increased temperature had also consequences at the population level; an established population model parameterized using data from the study to evaluate the influence of temperature and plant secondary compounds on the regulation of the sawfly predict that, depending on food quality, outbreak risks could both decrease and increase in a warmer climate. If so, effects of plant secondary compounds will play an increasing role for larval survival in a future warmer climate and temperature will, via multitrophic effects on larval survival, strongly influence how sawfly and other insect populations are regulated.

Kühsel, S., and N. Blüthgen. 2015. **High diversity stabilizes the thermal resilience of pollinator communities in intensively managed grasslands.** Nature Communications 6:7989.

Abstract. The resilience of ecosystems depends on the diversity of species and their specific responses to environmental variation. Here we show that the diversity of climatic responses across species contributes to a higher projected resilience of species-rich pollinator communities in real-world ecosystems despite land-use intensification. We determined the thermal niche of 511 pollinator species (flies, bees, beetles and butterflies) in 40 grasslands. Species in intensively used grasslands have broader thermal niches and are also more complementary in their thermal optima. The observed increase in thermal resilience with land-use intensification is mainly driven by the dominant flies that prefer cooler temperatures and compensate for losses of other taxa. Temperature explained 84% of the variation in pollinator activity across species and sites. Given the key role of temperature, quantifying the diversity of thermal responses within functional groups is a promising approach to assess the vulnerability of ecosystems to land-use intensification and climate change.

Weed, A., B. Bentz, M. Ayres, and T. Holmes. 2015. **Geographically variable response of *Dendroctonus ponderosae* to winter warming in the western United States.** Landscape Ecology 30:1075-1093.

Abstract. Context. Milder winters have contributed to recent outbreaks of *Dendroctonus ponderosae* in Canada, but have not been evaluated as a factor permitting concurrent outbreaks across its large range (ca.1500 × 1500 km) in the western United States (US).

Objectives. We examined the trend in minimum air temperatures in *D. ponderosae* habitats across the western US and assessed whether warming winters explained the occurrence of outbreaks using physiological and population models.

Methods. We used climate data to analyze the history of minimum air temperatures and reconstruct physiological effects of cold on *D. ponderosae*. We evaluated relations between winter temperatures and beetle abundance using aerial detection survey data.

Results. Extreme winter temperatures have warmed by about 4 °C since 1960 across the western US. At the broadest scale, *D. ponderosae* population dynamics between 1997 and 2010 were unrelated to variation in minimum temperatures, but relations between cold and *D. ponderosae* dynamics varied among regions. In the 11 coldest ecoregions, lethal winter temperatures have become less frequent since the 1980s and beetle-caused tree mortality increased—consistent with the climatic release hypothesis. However, in the 12 warmer regions, recent epidemics cannot be attributed to warming winters because earlier winters were not cold enough to kill *D. ponderosae*.

Conclusions. There has been pronounced warming of winter temperatures throughout the western US, and this has reduced previous constraints on D. ponderosae abundance in some regions. However, other considerations are necessary to understand the broad extent of recent D. ponderosae epidemics in the western US.

Invasive Species

Stevens, J. T., and A. M. Latimer. 2015. **Snowpack, fire, and forest disturbance: interactions affect montane invasions by non-native shrubs.** Global Change Biology 21:2379-2393.

Abstract. Montane regions worldwide have experienced relatively low plant invasion rates, a trend attributed to increased climatic severity, low rates of disturbance, and reduced propagule pressure relative to lowlands. Manipulative experiments at elevations above the invasive range of non-native species can clarify the relative contributions of these mechanisms to montane invasion resistance, yet such experiments are rare. Furthermore, global climate change and land use changes are expected to cause decreases in snowpack and increases in disturbance by fire and forest thinning in montane forests. We examined the importance of these factors in limiting montane invasions using a field transplant experiment above the invasive range of two non-native lowland shrubs, Scotch broom (*Cytisus scoparius*) and Spanish broom (*Spartium junceum*), in the rain–snow transition zone of the Sierra Nevada of California. We tested the effects of canopy closure, prescribed fire, and winter snow depth on demographic transitions of each species. Establishment of both species was most likely at intermediate levels of canopy disturbance, but at this intermediate canopy level, snow depth had negative effects on winter survival of seedlings. We used matrix population models to show that an 86% reduction in winter snowfall would cause a 2.8-fold increase in population growth rates in Scotch broom and a 3.5-fold increase in Spanish broom. Fall prescribed fire increased germination rates, but decreased overall population growth rates by reducing plant survival. However, at longer fire return intervals, population recovery between fires is likely to keep growth rates high, especially under low snowpack conditions. Many treatment combinations had positive growth rates despite being above the current invasive range, indicating that propagule pressure, disturbance, and climate can all strongly affect plant invasions in montane regions. We conclude that projected reductions in winter snowpack and increases in forest

disturbance are likely to increase the risk of invasion from lower elevations.

Soils and Hydrology

Classen, A. T., M. K. Sundqvist, J. A. Henning, G. S. Newman, J. A. M. Moore, M. A. Cregger, L. C. Moorhead, and C. M. Patterson. 2015. **Direct and indirect effects of climate change on soil microbial and soil microbial-plant interactions: What lies ahead?** Ecosphere 6:art130.

Abstract. Global change is altering species distributions and thus interactions among organisms. Organisms live in concert with thousands of other species, some beneficial, some pathogenic, some which have little to no effect in complex communities. Since natural communities are composed of organisms with very different life history traits and dispersal ability it is unlikely they will all respond to climatic change in a similar way. Disjuncts in plant-pollinator and plant-herbivore interactions under global change have been relatively well described, but plant-soil microorganism and soil microbe-microbe relationships have received less attention. Since soil microorganisms regulate nutrient transformations, provide plants with nutrients, allow co-existence among neighbors, and control plant populations, changes in soil microorganism-plant interactions could have significant ramifications for plant community composition and ecosystem function. In this paper we explore how climatic change affects soil microbes and soil microbe-plant interactions directly and indirectly, discuss what we see as emerging and exciting questions and areas for future research, and discuss what ramifications changes in these interactions may have on the composition and function of ecosystems.

Crowther, T. W., S. M. Thomas, D. S. Maynard, P. Baldrian, K. Covey, S. D. Frey, L. T. A. van Diepen, and M. A. Bradford. 2015. **Biotic interactions mediate soil microbial feedbacks to climate change.** Proceedings of the National Academy of Sciences 112:7033-7038.

Abstract. Decomposition of organic material by soil microbes generates an annual global release of 50–75 Pg carbon to the atmosphere, ~7.5–9 times that of anthropogenic emissions worldwide. This process is sensitive to global change factors, which can drive carbon cycle–climate feedbacks with the potential to enhance atmospheric warming. Although the effects of interacting global change factors on soil microbial activity have been a widespread ecological focus, the regulatory effects of interspecific interactions are rarely considered in climate feedback studies. We explore the potential of soil animals to mediate microbial responses to warming and nitrogen enrichment within a long-term, field-based global change study. The combination of global change factors alleviated the bottom-up limitations on fungal growth, stimulating enzyme production and decomposition rates in the absence of soil animals. However, increased fungal biomass also stimulated consumption rates by soil invertebrates, restoring microbial process rates to levels observed under ambient conditions. Our results support the contemporary theory that top-down control in soil food webs is apparent only in the absence of bottom-up limitation. As such, when global change factors alleviate the bottom-up limitations on microbial activity, top-down control becomes an increasingly important regulatory force with the capacity to dampen the strength of positive carbon cycle–climate feedbacks

McHugh, P. A., R. M. Thompson, H. S. Greig, H. J. Warburton, and A. R. McIntosh. 2015. **Habitat size influences food web structure in drying streams.** Ecography 38:700-712.

Abstract. Biodiversity in running waters is threatened by an increased severity and incidence of low-flow extremes resulting from global climate change and a growing human demand for freshwater resources. Although it is unknown how and to what extent riverine communities will change in the face of these threats, considerable insight will be gained from efforts aimed at quantifying habitat size-related controls on the trophic relationships among taxa in streams experiencing extreme flow loss. Here we report on a detailed space-for-time survey of replicate stream food webs sampled along the perennial- to-drying continuum in each of fourteen different intermittent South Island, New Zealand streams. We quantified several structural attributes of food webs at fifty-eight sites, including two taxonomically-based metrics (web size, predator:prey ratio) and three stable isotope-based metrics (food chain length [FCL], trophic area, $\delta 13C$ range); we also quantified habitat size-, disturbance-, and resource-related covariates at each site. Food web structure varied widely across sample sites within and across study streams and much of this variation was explained by habitat size. Consistent with our predictions, we found that food webs became smaller (ca 30 to ca 15 taxa, ca 20-fold reduction in stable isotope-based trophic area) and shorter (maximum trophic position [FCL] from 4.1 to 2.0, 25%

reduction in predator:prey ratio) as we moved from the largest to smaller habitats. These results, and a comparison of our findings with those from a similar assessment conducted in perennial streams, suggest that there are perturbation thresholds which may trigger food web collapse when exceeded, and further imply that food webs may ultimately be ‘sized’ to minimum flows rather than average flow conditions. Our work provides a basis for making general predictions about how habitat contraction, and flow loss in particular, may affect communities and additionally provides insight on mechanisms warranting further attention.

Sala, O. E., L. A. Gherardi, and D. P. C. Peters. 2015. **Enhanced precipitation variability effects on water losses and ecosystem functioning: differential response of arid and mesic regions.** Climatic Change 131:213-227.

Abstract. Climate change will result in increased precipitation variability with more extreme events reflected in more frequent droughts as well as more frequent extremely wet conditions. The increase in precipitation variability will occur at different temporal scales from intra to inter-annual and even longer scales. At the intra-annual scale, extreme precipitation events will be interspersed with prolonged periods in between events. At the inter-annual scale, dry years or multi-year droughts will be combined with wet years or multi-year wet conditions. Consequences of this aspect of climate change for the functioning ecosystems and their ability to provide ecosystem services have been underexplored. We used a process-based ecosystem model to simulate water losses and soil-water availability at 35 grassland locations in the central US under 4 levels of precipitation variability (control, +25, +50 + 75 %) and six temporal scales ranging from intra- to multi-annual variability. We show that the scale of temporal variability had a larger effect on soil-water availability than the magnitude of variability, and that inter- and multi-annual variability had much larger effects than intra-annual variability. Further, the effect of precipitation variability was modulated by mean annual precipitation. Arid-semiarid locations receiving less than about 380 mm yr−1 mean annual precipitation showed increases in water availability as a result of enhanced precipitation variability while more mesic locations (>380 mm yr^{-1}) showed a decrease in soil water availability. The beneficial effects of enhanced variability in arid-semiarid regions resulted from a deepening of the soil-water availability profile and a reduction in bare soil evaporation. The deepening of the soil-water availability profile resulting from increase precipitation variability may promote future shifts in species

composition and dominance to deeper-rooted woody plants for ecosystems that are susceptible to state changes. The break point, which has a mean of 380-mm with a range between 440 and 350 mm, is remarkably similar to the 370-mm threshold of the inverse texture hypothesis, below which coarse-texture soils had higher productivity than fine-textured soils.

Strzepek, K., J. Neumann, J. Smith, J. Martinich, B. Boehlert, M. Hejazi, J. Henderson, C. Wobus, R. Jones, K. Calvin, D. Johnson, E. Monier, J. Strzepek, and J. H. Yoon. 2015. **Benefits of greenhouse gas mitigation on the supply, management, and use of water resources in the United States.** Climatic Change 131:127-141.

Abstract. Climate change impacts on water resources in the United States are likely to be far-reaching and substantial because the water is integral to climate, and the water sector spans many parts of the economy. This paper estimates impacts and damages from five water resource-related models addressing runoff, drought risk, economics of water supply/demand, water stress, and flooding damages. The models differ in the water system assessed, spatial scale, and unit of assessment, but together provide a quantitative and descriptive richness in characterizing water sector effects that no single model can capture. The results, driven by a consistent set of greenhouse gas (GHG) emission and climate scenarios, examine uncertainty from emissions, climate sensitivity, and climate model selection. While calculating the net impact of climate change on the water sector as a whole may be impractical, broad conclusions can be drawn regarding patterns of change and benefits of GHG mitigation. Four key findings emerge: 1) GHG mitigation substantially reduces hydro-climatic impacts on the water sector; 2) GHG mitigation provides substantial national economic benefits in water resources related sectors; 3) the models show a strong signal of wetting for the Eastern US and a strong signal of drying in the Southwest; and 4) unmanaged hydrologic systems impacts show strong correlation with the change in magnitude and direction of precipitation and temperature from climate models, but managed water resource systems and regional economic systems show lower correlation with changes in climate variables due to non-linearities created by water infrastructure and the socio-economic changes in non-climate driven water demand.

Snyder, C. D., N. P. Hitt, and J. A. Young. 2015. **Accounting for groundwater in stream fish thermal habitat responses to climate change.** Ecological Applications 25:1397-1419.

Abstract. Forecasting climate change effects on aquatic fauna and their habitat requires an understanding of how water temperature responds to changing air temperature (i.e., thermal sensitivity). Previous efforts to forecast climate effects on brook trout (*Salvelinus fontinalis*) habitat have generally assumed uniform air–water temperature relationships over large areas that cannot account for groundwater inputs and other processes that operate at finer spatial scales. We developed regression models that accounted for groundwater influences on thermal sensitivity from measured air–water temperature relationships within forested watersheds in eastern North America (Shenandoah National Park, Virginia, USA, 78 sites in nine watersheds). We used these reach-scale models to forecast climate change effects on stream temperature and brook trout thermal habitat, and compared our results to previous forecasts based upon large-scale models. Observed stream temperatures were generally less sensitive to air temperature than previously assumed, and we attribute this to the moderating effect of shallow groundwater inputs. Predicted groundwater temperatures from air–water regression models corresponded well to observed groundwater temperatures elsewhere in the study area. Predictions of brook trout future habitat loss derived from our fine-grained models were far less pessimistic than those from prior models developed at coarser spatial resolutions. However, our models also revealed spatial variation in thermal sensitivity within and among catchments resulting in a patchy distribution of thermally suitable habitat. Habitat fragmentation due to thermal barriers therefore may have an increasingly important role for trout population viability in headwater streams. Our results demonstrate that simple adjustments to air–water temperature regression models can provide a powerful and cost-effective approach for predicting future stream temperatures while accounting for effects of groundwater.

Fire

Enright, N. J., J. B. Fontaine, D. M. J. S. Bowman, R. A. Bradstock, and R. J. Williams. 2015. **Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes.** Frontiers in Ecology and the Environment 13:265-272.

Abstract. Projected effects of climate change across many ecosystems globally include more frequent disturbance by fire and reduced plant growth due to warmer (and especially drier) conditions. Such changes affect species – particularly fire-intolerant woody plants – by simultaneously reducing recruitment, growth, and survival. Collectively, these mechanisms may narrow the fire interval window compatible with population persistence, driving species to extirpation or extinction. We present a conceptual model of these combined effects, based on synthesis of the known impacts of climate change and altered fire regimes on plant demography, and describe a syndrome we term “interval squeeze”. This model predicts that interval squeeze will increase woody plant extinction risk and change ecosystem structure, composition, and carbon storage, especially in regions projected to become both warmer and drier. These predicted changes demand new approaches to fire management that will maximize the in situ adaptive capacity of species to respond to climate change and fire regime change.

Wang, X., D. Thompson, G. Marshall, C. Tymstra, R. Carr, and M. Flannigan. 2015. **Increasing frequency of extreme fire weather in Canada with climate change.** Climatic Change 130:573-586.

Abstract. In Canadian forests, the majority of burned area occurs on a small number of days of extreme fire weather. These days lie within the tail end of the distribution of fire weather, and are often the periods when fire suppression capacity is most challenged. We examined the historic and future frequency of such extreme fire weather events across 16 fire regime zones in the forested regions of Canada from 1970 to the year 2090. Two measurements are used to measure the extreme fire weather events, the 95th percentile of Fire Weather Index (FWI_{95}) and the number of spread days. The annual frequency of fire spread days is modelled to increase 35–400 % by 2050 with the greatest absolute increases occurring in the Boreal Plains of Alberta and Saskatchewan. The largest proportional increase in the number of spread days is modelled to occur in coastal and temperate forests. This large increase in spread days was found despite a modest average increase in FWI_{95}. Our findings suggest that the impact of future climate change in Canadian forests is sufficient to increase the number of days with active fire spread. Fire management agencies in coastal and temperate regions may need to adapt their planning and capacity to deal with proportionally larger changes to their fire weather regime compared to the already high fire management capacity found in drier continental regions.

Yang, J., P. Weisberg, D. Shinneman, T. Dilts, S. Earnst, and R. Scheller. 2015. **Fire modulates climate change response of simulated aspen distribution across topoclimatic gradients in a semi-arid montane landscape.** Landscape Ecology 30:1055-1073.

Abstract. Content. Changing aspen distribution in response to climate change and fire is a major focus of biodiversity conservation, yet little is known about the potential response of aspen to these two driving forces along topoclimatic gradients.

Objective. This study is set to evaluate how aspen distribution might shift in response to different climate-fire scenarios in a semi-arid montane landscape, and quantify the influence of fire regime along topoclimatic gradients.

Methods. We used a novel integration of a forest landscape succession and disturbance model (LANDIS-II) with a fine-scale climatic water deficit approach to simulate dynamics of aspen and associated conifer and shrub species over the next 150 years under various climate-fire scenarios.

Results. Simulations suggest that many aspen stands could persist without fire for centuries under current climate conditions. However, a simulated 2–5 °C increase in temperature caused a substantial reduction of aspen coverage at lower elevations and a modest increase at upper elevations, leading to an overall reduction of aspen range at the landscape level. Increasing fire activity may favor aspen increase at its upper elevation limits adjacent to coniferous forest, but may also favor reduction of aspen at lower elevation limits adjacent to xeric shrubland.

Conclusions. Our study highlights the importance of incorporating fine-scale terrain effects on climatic water deficit and ecohydrology when modeling species distribution response to climate change. This modeling study suggests that climate mitigation and adaptation

strategies that use fire would benefit from consideration of spatial context at landscape scales.

Yocom Kent, L. L., K. L. Shive, B. A. Strom, C. H. Sieg, M. E. Hunter, C. S. Stevens-Rumann, and P. Z. Fulé. 2015. **Interactions of fuel treatments, wildfire severity, and carbon dynamics in dry conifer forests.** Forest Ecology and Management 349:66-72.

Abstract. Wildfires have been increasing in size and severity over recent decades. Forest managers use fuel treatments, including tree thinning and prescribed burning, to reduce the risk of high-severity fire. The impact of fuel treatments on carbon dynamics is not fully understood; previous research indicates that because carbon is removed during fuel treatments, the net effect may not be a reduction of carbon lost in the case of wildfire. The Rodeo–Chediski Fire, which burned in Arizona in 2002, was one of the largest and most severe wildfires recorded in the southwestern United States. Our objectives were to quantify carbon in three pools (live overstory trees, standing snags, and forest floor debris) across a combination of burn severities and pre-fire treatments, 2 years and 8 years after the Rodeo–Chediski Fire. Treatments included prescribed (Rx) fire, a cut and burn treatment, and no treatment. We sampled 106 plots in 36 sites in our ponderosa pine-dominated study area. We found that treatments strongly influenced fire severity; high- and moderate-severity fire was reduced from 76% in untreated areas to 57% in Rx fire treatments and 38% in cut and burn treatments. Fire severity, year, and severity X year were significant factors affecting carbon in the three different pools across the landscape. Eight years post-fire, high-severity burned areas had only 58% of the total carbon (live + dead) that low-severity areas had, and only 3% of the live carbon. Live carbon increased over time in low-severity sites but decreased over time in high-severity sites. We conclude that fuel treatments can significantly influence fire severity, which in turn influences carbon pools. However, treatments may or may not reduce overall carbon loss from an ecosystem in the event of a wildfire given that treatments remove carbon too. Finally, long-term monitoring is important to gain a more complete understanding of post-fire carbon dynamics.

Sea Level Rise

Watson, C. S., N. J. White, J. A. Church, M. A. King, R. J. Burgette, and B. Legresy. 2015. **Unabated global mean sea-level rise over the satellite altimeter era.** Nature Climate Change 5:565-568.

Abstract. The rate of global mean sea-level (GMSL) rise has been suggested to be lower for the past decade compared with the preceding decade as a result of natural variability1, with an average rate of rise since 1993 of +3.2 ± 0.4 mm yr^{-1}. However, satellite-based GMSL estimates do not include an allowance for potential instrumental drifts (bias drift). Here, we report improved bias drift estimates for individual altimeter missions from a refined estimation approach that incorporates new Global Positioning System (GPS) estimates of vertical land movement (VLM). In contrast to previous results (for example, refs 6, 7), we identify significant non-zero systematic drifts that are satellite-specific, most notably affecting the first 6 years of the GMSL record. Applying the bias drift corrections has two implications. First, the GMSL rate (1993 to mid-2014) is systematically reduced to between +2.6 ± 0.4 mm yr^{-1} and +2.9 ± 0.4 mm yr^{-1}, depending on the choice of VLM applied. These rates are in closer agreement with the rate derived from the sum of the observed contributions, GMSL estimated from a comprehensive network of tide gauges with GPS-based VLM applied (updated from ref. 8) and reprocessed ERS-2/Envisat altimetry. Second, in contrast to the previously reported slowing in the rate during the past two decades, our corrected GMSL data set indicates an acceleration in sea-level rise (independent of the VLM used), which is of opposite sign to previous estimates and comparable to the accelerated loss of ice from Greenland and to recent projections, and larger than the twentieth-century acceleration.

Adaptation

Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly. 2015. **Integrated economic and climate projections for impact assessment.** Climatic Change 131:21-33.

Abstract. We designed scenarios for impact assessment that explicitly address policy choices and uncertainty in climate response. Economic projections and the resulting greenhouse gas emissions for the “no climate policy” scenario and two stabilization scenarios: at 4.5 W/m^2 and 3.7 W/m^2 by 2100 are provided. They can be used for a

broader climate impact assessment for the US and other regions, with the goal of making it possible to provide a more consistent picture of climate impacts, and how those impacts depend on uncertainty in climate system response and policy choices. The long-term risks, beyond 2050, of climate change can be strongly influenced by policy choices. In the nearer term, the climate we will observe is hard to influence with policy, and what we actually see will be strongly influenced by natural variability and the earth system response to existing greenhouse gases. In the end, the nature of the system is that a strong effect of policy, especially directed toward long-lived GHGs, will lag by 30 to 40 years its implementation

Truitt, A. M., E. F. Granek, M. J. Duveneck, K. A. Goldsmith, M. P. Jordan, and K. C. Yazzie. 2015. **What is novel about novel ecosystems: managing change in an ever-changing world.** Environmental Management 55:1217-1226.

Abstract. Influenced by natural climatic, geological, and evolutionary changes, landscapes and the ecosystems within are continuously changing. In addition to these natural pressures, anthropogenic drivers have increasingly influenced ecosystems. Whether affected by natural or anthropogenic processes, ecosystems, ecological communities, and ecosystem functioning are dynamic and can lead to “novel” or “emerging” ecosystems. Current literature identifies several definitions of these ecosystems but lacks an unambiguous definition and framework for categorizing what constitutes a novel ecosystem and for informing decisions around best management practices. Here we explore the various definitions used for novel ecosystems, present an unambiguous definition, and propose a framework for identifying the most appropriate management option. We identify and discuss three approaches for managing novel ecosystems: managing against, tolerating, and managing for these systems, and we provide real-world examples of each approach. We suggest that this framework will allow managers to make thoughtful decisions about which strategy is most appropriate for each unique situation, to determine whether the strategy is working, and to facilitate decision-making when it is time to modify the management approach.