Climate Change Quarterly: Spring 2015

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

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Climate and 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.

Fischer, E. M., and R. Knutti. 2015. **Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes.** Nature Climate Change 5: 560-564.

Abstract. Climate change includes not only changes in mean climate but also in weather extremes. For a few prominent heatwaves and heavy precipitation events a human contribution to their occurrence has been demonstrated. Here we apply a similar framework but estimate what fraction of all globally occurring heavy precipitation and hot extremes is attributable to warming. We show that at the present-day warming of 0.85 °C about 18% of the moderate daily precipitation extremes over land are attributable to the observed temperature increase since pre-industrial times, which in turn primarily results from human influence. For 2 °C of warming the fraction of precipitation extremes attributable to human influence rises to about 40%. Likewise, today about 75% of the moderate daily hot extremes over land are attributable to warming. It is the most rare and extreme events for which the largest fraction is anthropogenic, and that contribution increases nonlinearly with further warming. The approach introduced here is robust owing to its global perspective, less sensitive to model biases than alternative methods and informative for mitigation policy, and thereby complementary to single-event attribution. Combined with information on vulnerability and exposure, it serves as a scientific basis for assessment of global risk from extreme weather, the discussion of mitigation targets, and liability considerations.

Johansson, D. J. A., B. C. O'Neill, C. Tebaldi, and O. Haggstrom. 2015. **Equilibrium climate sensitivity in light of observations over the warming hiatus.** Nature Climate Change 5: 449-453.

Abstract. A key uncertainty in projecting future climate change is the magnitude of equilibrium climate sensitivity (ECS), that is, the eventual increase in global annual average surface temperature in response to a doubling of atmospheric CO_2 concentration. The lower bound of the likely range for ECS given in the IPCC Fifth Assessment Report (AR5; refs 1, 2) was revised downwards to 1.5 °C, from 2 °C in its previous report, mainly as an effect of considering observations over the warming hiatus—the period of slowdown of global average temperature increase since the early 2000s. Here we analyse how estimates of ECS change as observations accumulate over time and estimate the contribution of potential causes to the hiatus. We find that including observations over the hiatus reduces the most likely value for ECS from 2.8 °C to 2.5 °C, but that the lower bound of the

90% range remains stable around 2 °C. We also find that the hiatus is primarily attributable to El Niño/Southern Oscillation-related variability and reduced solar forcing.

Mountain Research Initiative EDW Working Group. 2015. **Elevation-dependent warming in mountain regions of the world.** Nature Climate Change 5: 424-430.

Abstract. There is growing evidence that the rate of warming is amplified with elevation, such that high-mountain environments experience more rapid changes in temperature than environments at lower elevations. Elevation-dependent warming (EDW) can accelerate the rate of change in mountain ecosystems, cryospheric systems, hydrological regimes and biodiversity. Here we review important mechanisms that contribute towards EDW: snow albedo and surface-based feedbacks; water vapour changes and latent heat release; surface water vapour and radiative flux changes; surface heat loss and temperature change; and aerosols. All lead to enhanced warming with elevation (or at a critical elevation), and it is believed that combinations of these mechanisms may account for contrasting regional patterns of EDW. We discuss future needs to increase knowledge of mountain temperature trends and their controlling mechanisms through improved observations, satellite-based remote sensing and model simulations.

Roberts, C. D., M. D. Palmer, D. McNeall, and M. Collins. 2015. **Quantifying the likelihood of a continued hiatus in global warming.** Nature Climate Change 5: 337-342.

Abstract. Since the end of the twentieth century, global mean surface temperature has not risen as rapidly as predicted by global climate models (GCMs). This discrepancy has become known as the global warming ‘hiatus’ and a variety of mechanisms have been proposed to explain the observed slowdown in warming. Focusing on internally generated variability, we use pre-industrial control simulations from an observationally constrained ensemble of GCMs and a statistical approach to evaluate the expected frequency and characteristics of variability-driven hiatus periods and their likelihood of future continuation. Given an expected forced warming trend of ~0.2 K per decade, our constrained ensemble of GCMs implies that the probability of a variability-driven 10-year hiatus is ~10%, but less than 1% for a 20-year hiatus. Although the absolute probability of a 20-year hiatus is small, the probability that an existing 15-year hiatus will continue another five years is much higher (up to 25%). Therefore, given the recognized contribution of internal climate variability to the reduced rate of global warming during the past 15 years, we should not be surprised if the current hiatus continues until the end of the decade. Following the termination of a variability-driven hiatus, we also show that there is an increased likelihood of accelerated global warming associated with release of heat from the sub-surface ocean and a reversal of the phase of decadal variability in the Pacific Ocean.

Smith, S. J., J. Edmonds, C. A. Hartin, A. Mundra, and K. Calvin. 2015. **Near-term acceleration in the rate of temperature change.** Nature Climate Change 5:333-336.

Abstract. Anthropogenically driven climate changes, which are expected to impact human and natural systems, are often expressed in terms of global-mean temperature. The rate of climate change over multi-decadal scales is also important, with faster rates of change resulting in less time for human and natural systems to adapt. We find that present trends in greenhouse-gas and aerosol emissions are now moving the Earth system into a regime in terms of multi-decadal rates of change that are unprecedented for at least the past 1,000 years. The rate of global-mean temperature increase in the CMIP5 (ref. 3) archive over 40-year periods increases to 0.25 ± 0.05 °C (1σ) per decade by 2020, an average greater than peak rates of change during the previous one to two millennia. Regional rates of change in Europe, North America and the Arctic are higher than the global average. Research on the impacts of such near-term rates of change is urgently needed.

van Nes, E. H., M. Scheffer, V. Brovkin, T. M. Lenton, H. Ye, E. Deyle, and G. Sugihara. 2015. **Causal feedbacks in climate change.** Nature Climate Change 5: 445-448.

Abstract. The statistical association between temperature and greenhouse gases over glacial cycles is well documented, but causality behind this correlation remains difficult to extract directly from the data. A time lag of CO_2 behind Antarctic temperature—originally thought to hint at a driving role for temperature—is absent at the last deglaciation, but recently confirmed at the last ice age inception and the end of the earlier termination II (ref. 7). We show that such variable time lags are typical for complex nonlinear systems such as the climate, prohibiting straightforward use of correlation lags to infer causation. However, an insight from dynamical systems theory now allows us to circumvent the classical challenges of unravelling causation from multivariate time series. We build on this insight to demonstrate directly from ice-core data that, over glacial–interglacial timescales, climate dynamics are largely driven by internal Earth system mechanisms, including a marked positive feedback effect from temperature variability on greenhouse-gas concentrations.

Carbon and Carbon Storage

Ahlström, A., M. R. Raupach, G. Schurgers, B. Smith, A. Arneth, M. Jung, M. Reichstein, J. G. Canadell, P. Friedlingstein, A. K. Jain, E. Kato, B. Poulter, S. Sitch, B. D. Stocker, N. Viovy, Y. P. Wang, A. Wiltshire, S. Zaehle, and N. Zeng. 2015. **The dominant role of semi-arid ecosystems in the trend and variability of the land CO_2 sink.** Science 348: 895-899.

Abstract. The growth rate of atmospheric carbon dioxide (CO_2) concentrations since industrialization is characterized by large interannual variability, mostly resulting from variability in CO_2 uptake by terrestrial ecosystems (typically termed carbon sink). However, the contributions of regional ecosystems to that variability are not well known. Using an ensemble of ecosystem and land-surface models and an empirical observation-based product of global gross primary production, we show that the mean sink, trend, and interannual variability in CO_2 uptake by terrestrial ecosystems are dominated by distinct biogeographic regions. Whereas the mean sink is dominated by highly productive lands (mainly tropical forests), the trend and interannual variability of the sink are dominated by semi-arid ecosystems whose carbon balance is strongly associated with circulation-driven variations in both precipitation and temperature.

Keiluweit, M., J. J. Bougoure, P. S. Nico, J. Pett-Ridge, P. K. Weber, and M. Kleber. 2015. **Mineral protection of soil carbon counteracted by root exudates.** Nature Climate Change 5: 588-595.

Abstract. Multiple lines of existing evidence suggest that climate change enhances root exudation of organic compounds into soils. Recent experimental studies show that increased exudate inputs may cause a net loss of soil carbon. This stimulation of microbial carbon mineralization (‘priming’) is commonly rationalized by the assumption that exudates provide a readily bioavailable supply of energy for the

decomposition of native soil carbon (co-metabolism). Here we show that an alternate mechanism can cause carbon loss of equal or greater magnitude. We find that a common root exudate, oxalic acid, promotes carbon loss by liberating organic compounds from protective associations with minerals. By enhancing microbial access to previously mineral-protected compounds, this indirect mechanism accelerated carbon loss more than simply increasing the supply of energetically more favourable substrates. Our results provide insights into the coupled biotic–abiotic mechanisms underlying the 'priming' phenomenon and challenge the assumption that mineral-associated carbon is protected from microbial cycling over millennial timescales.

Santín, C., S. H. Doerr, C. M. Preston, and G. González-Rodríguez. 2015. **Pyrogenic organic matter production from wildfires: a missing sink in the global carbon cycle.** Global Change Biology 21: 1621-1633.

Abstract. Wildfires release substantial quantities of carbon (C) into the atmosphere but they also convert part of the burnt biomass into pyrogenic organic matter (PyOM). This is richer in C and, overall, more resistant to environmental degradation than the original biomass, and, therefore, PyOM production is an efficient mechanism for C sequestration. The magnitude of this C sink, however, remains poorly quantified, and current production estimates, which suggest that ~1-5% of the C affected by fire is converted to PyOM, are based on incomplete inventories. Here, we quantify, for the first time, the complete range of PyOM components found in-situ immediately after a typical boreal forest fire. We utilized an experimental high-intensity crown fire in a jack pine forest (*Pinus banksiana*) and carried out a detailed pre- and postfire inventory and quantification of all fuel components, and the PyOM (i.e., all visually charred, blackened materials) produced in each of them. Our results show that, overall, 27.6% of the C affected by fire was retained in PyOM (4.8 ± 0.8 t C ha^{-1}), rather than emitted to the atmosphere (12.6 ± 4.5 t C ha^{-1}). The conversion rates varied substantially between fuel components. For down wood and bark, over half of the C affected was converted to PyOM, whereas for forest floor it was only one quarter, and less than a tenth for needles. If the overall conversion rate found here were applicable to boreal wildfire in general, it would translate into a PyOM production of ~100 Tg C yr^{-1} by wildfire in the global boreal regions, more than five times the amount estimated previously. Our findings suggest that PyOM production from boreal wildfires, and potentially also from other fire-prone ecosystems, may have been underestimated and that its quantitative importance as a C sink warrants its inclusion in the global C budget estimates.

van Kooten, G. C., T. N. Bogle, and F. P. de Vries. 2015. **Forest carbon offsets revisited: shedding light on darkwoods.** Forest Science 61: 370-380.

Abstract. This paper investigates the viability of carbon offset credits created through forest conservation and preservation. A detailed forest management model based on a case study of a forest estate in southeastern British Columbia, owned by The Nature Conservancy of Canada (NCC) is used to demonstrate the challenging nature of estimating forest carbon offsets. For example, the NCC management plan creates substantial carbon offset credits because the counterfactual is that of a private forest liquidator, but when sustainable management of the site is assumed, the commercial operator would sequester much more carbon than under the NCC plan. The broader message is that the creation of carbon offsets is highly sensitive to ex ante assumptions and whether physical carbon is discounted. We demonstrate that more carbon gets stored in wood products as the discount rate on carbon rises (addressing climate change is more urgent). A high discount rate on carbon favors greater harvests and processing of biomass into products, while a low rate favors reduced harvest intensity. Further, since carbon credits earned by protecting forests may find their way onto world carbon markets, they lower the costs of emitting CO2 while contributing little to mitigating climate change.

Greenhouse Gas Emissions

Tian, H., G. Chen, C. Lu, X. Xu, D. Hayes, W. Ren, S. Pan, D. Huntzinger, and S. Wofsy. 2015. **North American terrestrial CO_2 uptake largely offset by CH_4 and N_2O emissions: toward a full accounting of the greenhouse gas budget.** Climatic Change 129: 413-426.

Abstract. The terrestrial ecosystems of North America have been identified as a sink of atmospheric CO_2 though there is no consensus on the magnitude. However, the emissions of non-CO_2 greenhouse gases (CH_4 and N_2O) may offset or even overturn the climate cooling effect induced by the CO_2 sink. Using a coupled biogeochemical model, in this study, we have estimated the combined global warming potentials (GWP) of CO_2, CH_4 and N_2O fluxes in North American terrestrial ecosystems and quantified the relative contributions of environmental factors to the GWP changes during 1979–2010. The uncertainty range for contemporary global warming potential has been quantified by synthesizing the existing estimates from inventory, forward modeling, and inverse modeling approaches. Our “best estimate” of net GWP for CO_2, CH_4 and N_2O fluxes was −0.50 ± 0.27 Pg CO_2 eq/year (1 Pg = 1015 g) in North American terrestrial ecosystems during 2001–2010. The emissions of CH_4 and N_2O from terrestrial ecosystems had offset about two thirds (73 % ± 14 %) of the land CO_2 sink in the North American continent, showing large differences across the three countries, with offset ratios of 57 % ± 8 % in US, 83 % ± 17 % in Canada and 329 % ± 119 % in Mexico. Climate change and elevated tropospheric ozone concentration have contributed the most to GWP increase, while elevated atmospheric CO_2 concentration have contributed the most to GWP reduction. Extreme drought events over certain periods could result in a positive GWP. By integrating the existing estimates, we have found a wide range of uncertainty for the combined GWP. From both climate change science and policy perspectives, it is necessary to integrate ground and satellite observations with models for a more accurate accounting of these three greenhouse gases in North America.

Phenology Changes

Wang, C., R. Cao, J. Chen, Y. Rao, and Y. Tang. 2015. **Temperature sensitivity of spring vegetation phenology correlates to within-spring warming speed over the Northern Hemisphere.** Ecological Indicators 50: 62-68.

Abstract. The inter-annual shift of spring vegetation phenology relative to per unit change of preseason temperature, referred to as temperature sensitivity (days $°C^{-1}$), quantifies the response of spring phenology to temperature change. Temperature sensitivity was found to differ greatly among vegetation from different environmental conditions. Understanding the large-scale spatial pattern of temperature sensitivity and its underlying determinant will greatly improve our ability to predict spring phenology. In this study, we investigated the temperature sensitivity for natural ecosystems over the North Hemisphere (north of 30°N), based on the vegetation phenological date estimated from NDVI time-series data provided by the Advanced Very High Resolution Radiometer (AVHRR) and the

corresponding climate dataset. We found a notable longitudinal change pattern with considerable increases of temperature sensitivity from inlands to most coastal areas and a less obvious latitudinal pattern with larger sensitivity in low latitude area. This general spatial variation in temperature sensitivity is most strongly associated with the within-spring warming speed (WWS; $r = 0.35$, $p < 0.01$), a variable describing the increase speed of daily mean temperature during spring within a year, compared with other factors including the mean spring temperature, spring precipitation and mean winter temperature. These findings suggest that the same magnitude of warming will less affect spring vegetation phenology in regions with higher WWS, which might partially reflect plants' adaption to local climate that prevents plants from frost risk caused by the advance of spring phenology. WWS accounts for the spatial variation in temperature sensitivity and should be taken into account in forecasting spring phenology and in assessing carbon cycle under the projected climate warming.

Species Range Changes

Klassen, H. A., and P. J. Burton. 2015. **Climatic characterization of forest zones across administrative boundaries improves conservation planning.** Applied Vegetation Science 18:343-356.

Abstract. Aim. This paper demonstrates methods to extend standardized vegetation zone descriptions and mapped distributions across political boundaries. An extended climate niche for North America's Coastal Douglas-fir (CDF) forest zone is determined and projected to evaluate its potential distribution under a changing climate and to identify climate refugia for conservation planning.

Location. Pacific Northwest temperate rain forest in British Columbia (BC), CA, and nearby Washington (WA) and Oregon (OR), US.

Methods. Using a combination of ecosystem polygon mapping and ecological plot data with climate interpolation tools, forests characterized as CDF under BC's biogeoclimatic ecosystem classification system were identified in the neighbouring US. Current (baseline) limits to CDF distribution were identified and used to map its potential distribution and climate refugia under future climate conditions using ensemble Global Climate Model projections.

Results. The extended CDF climate niche covers 76 725 km2 under baseline conditions, with the majority of the area in the Pacific Northwest US. The extended CDF forest zone includes a vegetation assemblage consistent with existing definitions of BC's CDF moist maritime subzone, but also an additional vegetation assemblage representing a drier maritime subzone. Projections of future climate suggest a northerly shift (~150 km) and a decrease (−91.5%) in overall CDF area. Climate refugia are projected for discontinuous patches of CDF forest on Vancouver Island and adjacent mainland.

Conclusions. This project combined georeferenced ecological plot data and digital maps, thereby facilitating the international mapping of ecosystem distributions in adjacent administrative areas that do not currently use the same ecosystem classification and mapping systems. This approach and the concept of climate niche definition, distribution and persistence are applicable to the management, restoration and conservation of plant communities, particularly in evaluating future ecosystem range shifts and disruptions associated with a changing climate. The potential for dramatic reductions in the range of the Coastal Douglas-fir zone, with persistence in <15% of its current area, suggest that most of the extended CDF zone is marginally suitable for the characteristic CDF ecosystems and that slight shifts in climate or disturbance regime may greatly alter the character of the vegetation. The full climatic niche for British Columbia's Coastal Douglas-fir forest zone is determined from its mapped distribution and georeferenced plot data in the neighbouring USA. A new subzone is characterized, and the potential distribution of the extended zone is projected under a changing climate to identify climate refugia. For sensitive ecosystems with multi-jurisdictional distributions, this approach helps focus conservation efforts.

Kroiss, S. J., and J. HilleRisLambers. 2015. **Recruitment limitation of long-lived conifers: implications for climate change responses.** Ecology 96:1286-1297.

Abstract. Seed availability and suitable microsites for germination are likely to severely constrain the responses of plant species to climate change, especially at and beyond range edges. For example, range shifts may be slow if seed availability is low at range edges due to low parent-tree abundance or reduced fecundity. Even when seeds are available, climatic and biotic factors may further limit the availability of suitable microsites for recruitment. Unfortunately, the importance of seed and microsite limitation during range shifts remains unknown, since few studies have examined both factors simultaneously,

particularly across species' ranges. To address this issue, we assessed seed availability and the factors influencing germination for six conifer species across a large environmental gradient encompassing their elevational ranges. Specifically, we assessed (1) how parent-tree abundance influences annual seed availability; (2) how seed limitation varies across species' ranges; (3) how climatic and biotic factors affect germination; and (4) how seed and suitable microsite availability covary annually within and among species. We found that seed availability declined toward species' upper range edges for most species, primarily due to low parent-tree abundance rather than declining fecundity. Range expansions are thus likely to be lagged with respect to climate change, as long generation times preclude rapid increases in tree density. Negative impacts of canopy cover on germination rates suggest range shifts will further be slowed by competition with existing vegetation. Moreover, years of high seed production were generally correlated among species, but not correlated with the availability of suitable microsites, implying that seedling competition and the interaction between seed and microsite limitation will further constrain recruitment. However, the nature of microsite limitation varied strongly between treeline and low-elevation species due to differing responses to snowpack duration and competition, suggesting that treeline species may be quicker to shift their ranges in response to warming than low-elevation species. In all, our results demonstrate that seed and microsite limitation will likely result in lagged responses to climate change but with differences among species leading to complex range shift dynamics.

Menuz, D. R., K. M. Kettenring, C. P. Hawkins, and D. R. Cutler. 2015. **Non-equilibrium in plant distribution models – only an issue for introduced or dispersal limited species?** Ecography 38: 231-240.

Abstract. Species distribution models rely on the assumption that species' distributions are at equilibrium with environmental conditions within a region – i.e. they occur in all suitable habitats. If this assumption holds, species occurrence should be predictable from measures of the environment. Introduced species may be poor candidates for distribution models due to their presumed lack of equilibrium within the landscapes they occupy, although predicting their potential distributions is often of critical importance to natural resource managers. We determined if the accuracy of species distribution models differed between 17 native and 17 introduced riparian plant species in the western United States. We also assessed if model accuracy was associated with both environmental and biological factors that can influence dispersal. We used Random Forests to model species distributions and linear regression to determine if model accuracy was associated with dispersal-related traits. Model accuracy for introduced species was higher than that for native species. Dispersal-related traits did not affect model accuracy or improvement, though two other traits, family affiliation and rarity on the landscape, did have an effect. Distance-based measures of dispersal potential improved model fit equally for both native and introduced species and for species with a variety of dispersal traits, suggesting that the importance of regional propagule pressure is relatively constant across species with different dispersal opportunities. Several lines of future questioning are suggested by our results, including why introduced species may in some cases produce more accurate distribution models than native species and how species dispersal traits relate to distribution model accuracy at different spatial scales.

Wüest, R. O., A. Antonelli, N. E. Zimmermann, and H. P. Linder. 2015. **Available climate regimes drive niche diversification during range expansion.** The American Naturalist 185: 640-652.

Abstract. Climate is a main predictor of biodiversity on a global scale, yet how climate availability affects niche evolution remains poorly explored. Here we assess how intercontinental climate differences may affect the evolution of climate niches and suggest three possible processes: niche truncation along major environmental gradients, intercontinental differences in available climate causing differences in selective regimes, and niche shifts associated with long-distance dispersals leading to a pattern of punctuated evolution. Using the globally distributed danthonioid grasses, we show significant niche differentiation among continents and several instances of niche truncation. The comparison of inferred selective regimes with differences in available climatic space among continents demonstrates adaptation resulting from opportunistic evolution toward available climatic space. Our results suggest that niche evolution in this clade is punctuated, consistent with accelerated niche evolution after long-distance dispersal events. Finally, we discuss how intrinsic constraints (genetic, developmental, or functional) and biotic interactions could have interacted with these three processes during range expansion. Integrating these mechanisms could improve predictions for invasive taxa and long-term evolutionary responses of expanding clades to climate change.

Biodiversity

De Keersmaecker, W., S. Lhermitte, L. Tits, O. Honnay, B. Somers, and P. Coppin. 2015. **A model quantifying global vegetation resistance and resilience to short-term climate anomalies and their relationship with vegetation cover.** Global Ecology and Biogeography 24: 539-548.

Abstract. Aim. In order to mitigate the ecological, economical and social consequences of future climate change, we must understand and quantify the response of vegetation to short-term climate anomalies. There is currently no model that quantifies vegetation resistance and resilience at a global scale while simultaneously taking climate variability into account. The goals of this study were therefore to develop a standardized indicator of short-term vegetation resilience and resistance to drought and temperature anomalies, and to improve our understanding of vegetation resistance and resilience in drought-sensitive areas by linking metrics of vegetation stability to the percentage of tree cover, non-tree vegetation and bare soil.

Location. Global.

Methods. The deviation of vegetation behaviour from expectations was quantified using anomalies in the normalized difference vegetation index (NDVI) and modelled as a function of (1) past NDVI anomalies, (2) an instantaneous drought indicator and (3) temperature anomalies. Metrics of resistance and resilience were then extracted from the model and related to the percentages of bare soil, non-tree vegetation and tree cover.

Results. Comparisons of the globally derived resilience and resistance metrics showed low resilience and low resistance to drought in semi-arid areas, low resistance to negative temperature anomalies in high-latitude areas, and low resistance to positive temperature anomalies in the Sahel and Australia. In drought-sensitive areas, resilience was highest for vegetation types with 3–20% bare soil and 5–15% tree cover.

Main conclusions. Our ARx model is the first to simultaneously derive vegetation resistance and resilience metrics at a global scale, explicitly taking into account the spatial variability of short-term climate anomalies and data reliability. Its results highlight the impact of tree cover, non-tree vegetation and bare soil on vegetation resilience.

Munson, S. M., R. H. Webb, D. C. Housman, K. E. Veblen, K. E. Nussear, E. A. Beever, K. B. Hartney, M. N. Miriti, S. L. Phillips, R. E. Fulton, and N. G. Tallent. 2015. **Long-term plant responses to climate are moderated by biophysical attributes in a North American desert.** Journal of Ecology 103: 657-668.

Abstract. Recent elevated temperatures and prolonged droughts in many already water-limited regions throughout the world, including the southwestern United States, are likely to intensify according to future climate-model projections. This warming and drying can negatively affect perennial vegetation and lead to the degradation of ecosystem properties.

To better understand these detrimental effects, we formulate a conceptual model of dryland ecosystem vulnerability to climate change that integrates hypotheses on how plant species will respond to increases in temperature and drought, including how plant responses to climate are modified by landscape, soil and plant attributes that are integral to water availability and use. We test the model through a synthesis of fifty years of repeat measurements of perennial plant species cover in large permanent plots across the Mojave Desert, one of the most water-limited ecosystems in North America.

Plant species ranged in their sensitivity to precipitation in different seasons, capacity to increase in cover with high precipitation and resistance to decrease in cover with low precipitation.

Our model successfully explains how plant responses to climate are modified by biophysical attributes in the Mojave Desert. For example, deep-rooted plants were not as vulnerable to drought on soils that allowed for deep-water percolation, whereas shallow-rooted plants were better buffered from drought on soils that promoted water retention near the surface.

Synthesis. Our results emphasize the importance of understanding climate–vegetation relationships in the context of biophysical attributes that influence water availability and provide an important forecast of climate-change effects, including plant mortality and land degradation in dryland regions throughout the world.

Pacifici, M., W. B. Foden, P. Visconti, J. E. M. Watson, S. H. M. Butchart, K. M. Kovacs, B. R. Scheffers, D. G. Hole, T. G. Martin, H. R. Akcakaya, R. T. Corlett, B. Huntley, D. Bickford, J. A. Carr, A. A. Hoffmann, G. F. Midgley, P. Pearce-Kelly, R. G. Pearson, S. E. Williams, S. G. Willis, B. Young, and C. Rondinini. 2015. **Assessing species vulnerability to climate change.** Nature Climate Change 5: 215-224.

Abstract. The effects of climate change on biodiversity are increasingly well documented, and many methods have been developed to assess species' vulnerability to climatic changes, both ongoing and projected in the coming decades. To minimize global biodiversity losses, conservationists need to identify those species that are likely to be most vulnerable to the impacts of climate change. In this Review, we summarize different currencies used for assessing species' climate change vulnerability. We describe three main approaches used to derive these currencies (correlative, mechanistic and trait-based), and their associated data requirements, spatial and temporal scales of application and modelling methods. We identify strengths and weaknesses of the approaches and highlight the sources of uncertainty inherent in each method that limit projection reliability. Finally, we provide guidance for conservation practitioners in selecting the most appropriate approach(es) for their planning needs and highlight priority areas for further assessments.

Urban, M. C. 2015. **Accelerating extinction risk from climate change.** Science 348: 571-573.

Abstract. Current predictions of extinction risks from climate change vary widely depending on the specific assumptions and geographic and taxonomic focus of each study. I synthesized published studies in order to estimate a global mean extinction rate and determine which factors contribute the greatest uncertainty to climate change–induced extinction risks. Results suggest that extinction risks will accelerate with future global temperatures, threatening up to one in six species under current policies. Extinction risks were highest in South America, Australia, and New Zealand, and risks did not vary by taxonomic group. Realistic assumptions about extinction debt and dispersal capacity substantially increased extinction risks. We urgently need to adopt strategies that limit further climate change if we are to avoid an acceleration of global extinctions.

Forest Vegetation

Bormann, B. T., R. L. Darbyshire, P. S. Homann, B. A. Morrissette, and S. N. Little. 2015. **Managing early succession for biodiversity and long-term productivity of conifer forests in southwestern Oregon.** Forest Ecology and Management 340: 114-125.

Abstract. Early-successional stages have been truncated and altered in many western U.S. forest landscapes by planting conifers, controlling competing vegetation, suppressing fire, and focusing on maintaining late-seral species and undisturbed riparian zones. Declining area of early-successional stages may be reducing resilience and sustainability on landscapes that experience elevated disturbance related to future climate changes. In this study, two post-harvest early-successional treatments were compared to each other and to two mature-forest treatments using 20 years of evidence from replicated 7-ha experimental units in a southwestern Oregon forest dominated by Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco). One early-successional treatment (Douglas-fir plantation) planted Douglas-fir and was followed by a brushing to reduce hardwood competition to move quickly to the conifer stem-exclusion stage; the other (Early-seral plantation) favored natural sprouting and regeneration of hardwood shrubs and trees and planted scattered knobcone pines (*Pinus attenuata* Lemmon) and Douglas-fir. Plant diversity in the Early-seral plantation was 56% (year 2) and 26% (year 6) higher than in the Douglas-fir plantation. Both early-successional treatments far exceeded plant diversity in Unaltered and Thinned mature stands. Fifteen years of growth of shrubs and hardwood trees in the Early-seral plantation was remarkable, resulting in total aboveground biomass increment (18 Mg ha^{-1} yr^{-1}) double that of the Douglas-fir plantations. Important process effects related to primary productivity were noted: losses of soil organic matter from the B horizon in young Douglas-fir, and, after wildfire, increases in N_2-fixing plant cover in Early-seral plantation. The burl-sprouting and deep rooting of many hardwoods also created opportunities for nutrient retention and release from primary minerals as well as deep-profile water supply. Recognizing the importance of intentionally managing for shrubs and hardwood trees is particularly relevant at this site, because stand reconstruction and historical records indicate these species, along with knobcone pine, dominated the site for 40 years before the current mature Douglas-fir forest started gaining dominance. In contrast, the prolific natural regeneration of Douglas-fir after recent harvest and wildfire suggests that what comes back “naturally” in modern times will not allow this history to be repeated.

Carter, D. R., R. T. Fahey, K. Dreisilker, M. B. Bialecki, and M. L. Bowles. 2015. **Assessing patterns of oak regeneration and C storage in relation to restoration-focused management, historical land use, and potential trade-offs.** Forest Ecology and Management 343: 53-62.

Abstract. Restoration of composition, structure, and function in oak dominated ecosystems is the focus of management in temperate forests around the world. Land managers focused on oak ecosystem restoration are challenged by the legacy effects of complex land-use histories, urbanization, climate change, and potential stakeholder response to management. Trade-offs may exist between managing forests for climate mitigation (e.g., maximizing C storage or sequestration) and promoting shade-intolerant species historically associated with frequent or high-severity disturbances. This study assessed the potentially conflicting goals of sustained live biomass accrual and increased oak regeneration in the East Woods Natural Area at The Morton Arboretum in Lisle, IL, USA. We evaluated how biomass trends and oak regeneration were related to management regimes, land-use history, current stand structure and composition, and topoedaphic factors. Our results indicated no significant trade-off between sustained live biomass accrual and oak regeneration. Live biomass was increasing across the landscape (biomass increment averaged 18,186 kg ha^{-1} yr^{-1}) and was not strongly related to differences in management or land-use history. Oak regeneration was rare, especially beyond the seedling stage (~226 seedlings and 9 saplings ha^{-1}) and was also not strongly related to recent management. Our results indicate that even 20+ years of annual prescribed burning combined with understory thinning has failed to produce the open canopy conditions and high light availability that are necessary for successful oak recruitment. The absence of any trade-offs between biomass accrual and oak regeneration may, therefore, be largely related to the ineffectiveness of current management for promoting oak regeneration. More intensive management utilizing canopy manipulations could produce greater trade-offs, but is likely necessary to establish and release oak regeneration.

Dybzinski, R., C. E. Farrior, and S. W. Pacala. 2015. **Increased forest carbon storage with increased atmospheric CO_2 despite nitrogen limitation: a game-theoretic allocation model for trees in competition for nitrogen and light.** Global Change Biology 21: 1182-1196.

Abstract. Changes in resource availability often cause competitively driven changes in tree allocation to foliage, wood, and fine roots, either via plastic changes within individuals or through turnover of individuals with differing strategies. Here, we investigate how optimally competitive tree allocation should change in response to elevated atmospheric CO_2 along a gradient of nitrogen and light availability, together with how those changes should affect carbon storage in living biomass. We present a physiologically-based forest model that includes the primary functions of wood and nitrogen. From a tree's perspective, wood is an offensive and defensive weapon used against neighbors in competition for light. From a biogeochemical perspective, wood is the primary living reservoir of stored carbon. Nitrogen constitutes a tree's photosynthetic machinery and the support systems for that machinery, and its limited availability thus reduces a tree's ability to fix carbon. This model has been previously successful in predicting allocation to foliage, wood, and fine roots along natural productivity gradients. Using game theory, we solve the model for competitively optimal foliage, wood, and fine root allocation strategies for trees in competition for nitrogen and light as a function of CO_2 and nitrogen mineralization rate. Instead of down-regulating under nitrogen limitation, carbon storage under elevated CO_2 relative to carbon storage at ambient CO_2 is approximately independent of the nitrogen mineralization rate. This surprising prediction is a consequence of both increased competition for nitrogen driving increased fine root biomass and increased competition for light driving increased allocation to wood under elevated CO_2.

Silva Pedro, M., W. Rammer, and R. Seidl. 2015. **Tree species diversity mitigates disturbance impacts on the forest carbon cycle.** Oecologia 177: 619-630.

Abstract. Biodiversity fosters the functioning and stability of forest ecosystems and, consequently, the provision of crucial ecosystem services that support human well-being and quality of life. In particular, it has been suggested that tree species diversity buffers ecosystems against the impacts of disturbances, a relationship known as the “insurance hypothesis”. Natural disturbances have increased across Europe in recent decades and climate change is expected to amplify the frequency and severity of disturbance events. In this context, mitigating disturbance impacts and increasing the resilience of forest ecosystems is of growing importance. We have tested how tree species diversity modulates the impact of disturbance on net primary production and the total carbon stored in living biomass for a temperate forest landscape in Central Europe. Using the simulation model iLand to study the effect of different disturbance regimes on landscapes with varying levels of tree species richness, we found that increasing diversity generally reduces the disturbance impact on carbon storage and uptake, but that this effect weakens or even reverses with successional development. Our simulations indicate a clear positive relationship between diversity and resilience, with more diverse systems experiencing lower disturbance-induced variability in their trajectories of ecosystem functioning. We found that positive effects of tree species diversity are mainly driven by an increase in functional diversity and a modulation of traits related to recolonization and resource usage. The results of our study suggest that increasing tree species diversity could mitigate the effects of intensifying disturbance regimes on ecosystem functioning and improve the robustness of forest carbon storage and the role of forests in climate change mitigation.

Smith, J. M., J. Paritsis, T. T. Veblen, and T. B. Chapman. 2015. **Permanent forest plots show accelerating tree mortality in subalpine forests of the Colorado Front Range from 1982 to 2013.** Forest Ecology and Management 341: 8-17.

Abstract. Broad-scale studies have documented widespread increases in tree mortality coincident with warming in the western U.S.A., but variability in patterns and agents of mortality is poorly documented based on multi-decadal observations of permanently marked trees, particularly in Rocky Mountain subalpine forests. The current study examines temporal variability in tree mortality based on monitoring >5000 permanently marked trees across a range of topographic positions and stand ages from c. 120 to >550 years over a 31-year period in subalpine forests in the Colorado Front Range. This study documents accelerating rates of annual tree mortality for subalpine fir, Engelmann spruce, lodgepole pine, and limber pine from 1982 through 2013. Over the period from 1982 to 2013, annual mortality rates for all tree species combined increased from 0.36% to 1.03% in old stands (265 to >550 years since stand-initiating fires) and from 0.30% to 0.72% in young stands (120 years since fire). Tree populations at sites of topographically moister locations and where competition was less due to presence of canopy openings, experienced initially lower

rates of tree mortality but all populations experienced higher mortality rates after c. 2008. In comparison with the 1953–1994 period, the frequency of extreme high temperatures in early summer increased after the mid-1970s and more markedly after 2000. Over time, the contribution of early summer (July) conditions to annual drought has increased. This pattern of climatic variability has been coincident with and conducive to a two and a half fold increase in the average annualized tree mortality rates for the total tracked tree population from the relatively cool and wet 1982–1994 period to the warmer and drier 2008–2013 period. Tree mortality attributable to bark beetles over the 1982–2013 period was minor, except for western balsam bark beetle (*Dryocoetes confusus*) which since 2008 has accounted for about 12% of the subalpine fir deaths. Overall, our findings indicate that even in the absence of lethal bark beetle outbreaks conifer mortality, apparently associated with moisture stress, has recently increased in subalpine forests in the Colorado Front Range.

Zhang, J., S. Huang, and F. He. 2015. **Half-century evidence from western Canada shows forest dynamics are primarily driven by competition followed by climate.** Proceedings of the National Academy of Sciences 112: 4009-4014.

Abstract. Tree mortality, growth, and recruitment are essential components of forest dynamics and resiliency, for which there is great concern as climate change progresses at high latitudes. Tree mortality has been observed to increase over the past decades in many regions, but the causes of this increase are not well understood, and we know even less about long-term changes in growth and recruitment rates. Using a dataset of long-term (1958–2009) observations on 1,680 permanent sample plots from undisturbed natural forests in western Canada, we found that tree demographic rates have changed markedly over the last five decades. We observed a widespread, significant increase in tree mortality, a significant decrease in tree growth, and a similar but weaker trend of decreasing recruitment. However, these changes varied widely across tree size, forest age, ecozones, and species. We found that competition was the primary factor causing the long-term changes in tree mortality, growth, and recruitment. Regional climate had a weaker yet still significant effect on tree mortality, but little effect on tree growth and recruitment. This finding suggests that internal community-level processes—more so than external climatic factors—are driving forest dynamics.

Rangeland Vegetation

Floyd, M. L., W. H. Romme, M. E. Rocca, D. P. Hanna, and D. D. Hanna. 2015. **Structural and regenerative changes in old-growth piñon–juniper woodlands following drought-induced mortality.** Forest Ecology and Management 341: 18-29.

Abstract. Two decades of drought and rising temperatures have triggered bark beetle outbreaks and extensive mortality of Colorado piñon (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*) across the southwest US. For example from 2002 to 2005, over one-third of the piñons in Mesa Verde National Park's old-growth woodlands were killed by the bark beetle *Ips confusus* and other drought-related factors. Extensive wildfires have also burned through the Park over the last two decades, reducing the extent of old-growth woodlands by nearly one-half. We compared historical (1970–1990s) and recent (2005–2011) data to gauge the effects of the 2002–2005 mortality event on canopy structure, woody surface fuels, and tree recruitment. Large, mature piñons were the most susceptible to mortality; we measured significant reductions in piñon cover and diameter. Due to the loss of large trees, woodlands that were subjected to substantial mortality had reduced structural complexity relative to nearby unaffected stands. In a longitudinal fuels comparison, 2010–2011 fuels were compared to historical 1993 values in the same plots; we could not detect a change in woody fuel load. However when the 2010–2011 fuels are compared across mortality severity classes, there was a trend toward slightly greater 1–100 h, greater 1000 h fuel loads, and more litter in stands with higher levels of tree mortality. However, modeled surface fire behavior did not differ across mortality severity classes. Modeled crown fires needed higher wind speeds to spread from tree to tree in stands without tree mortality, but this is likely due to the inherently more open canopy structure in stands that resisted mortality rather than due to tree mortality per se. Post-mortality piñon reproduction and recruitment were recorded from 2005 to 2011 and compared with NPS monitoring data from 1975 to 1995. Cone production in 2005 was comparable to historical trends, but recent seedling and sapling densities were significantly below historical values. Yearly seedling and sapling density in 1975–2011 was positively correlated with precipitation during the sampling year and two years prior. The largest proportion of seedlings and saplings occurred under piñon or juniper canopies, and a smaller proportion under native shrubs. Given the loss of a substantial component of the adult trees, reduced stand structural complexity, and demonstrated need for moist conditions and nurse plants for effective recruitment,

these old-growth woodlands may be vulnerable to decline under future warm and dry climate projections. Management strategies focusing on maintaining structural features of both the overstory and understory could help provide conditions for sustainable recruitment and contribute to the goal of conservation of rare old-growth piñon–juniper woodlands.

Mowll, W., D. Blumenthal, K. Cherwin, A. Smith, A. Symstad, L. Vermeire, S. Collins, M. Smith, and A. Knapp. 2015. **Climatic controls of aboveground net primary production in semi-arid grasslands along a latitudinal gradient portend low sensitivity to warming.** Oecologia 177: 959-969.

Abstract. Although climate models forecast warmer temperatures with a high degree of certainty, precipitation is the primary driver of aboveground net primary production (ANPP) in most grasslands. Conversely, variations in temperature seldom are related to patterns of ANPP. Thus forecasting responses to warming is a challenge, and raises the question: how sensitive will grassland ANPP be to warming? We evaluated climate and multi-year ANPP data (67 years) from eight western US grasslands arrayed along mean annual temperature (MAT; ~7–14 °C) and mean annual precipitation (MAP; ~250–500 mm) gradients. We used regression and analysis of covariance to assess relationships between ANPP and temperature, as well as precipitation (annual and growing season) to evaluate temperature sensitivity of ANPP. We also related ANPP to the standardized precipitation evaporation index (SPEI), which combines precipitation and evapotranspiration to better represent moisture available for plant growth. Regression models indicated that variation in growing season temperature was negatively related to total and graminoid ANPP, but precipitation was a stronger predictor than temperature. Growing season temperature was also a significant parameter in more complex models, but again precipitation was consistently a stronger predictor of ANPP. Surprisingly, neither annual nor growing season SPEI were as strongly related to ANPP as precipitation. We conclude that forecasted warming likely will affect ANPP in these grasslands, but that predicting temperature effects from natural climatic gradients is difficult. This is because, unlike precipitation, warming effects can be positive or negative and moderated by shifts in the C3/C4 ratios of plant communities.

Ruppert, J. C., K. Harmoney, Z. Henkin, H. A. Snyman, M. Sternberg, W. Willms, and A. Linstädter. 2015. **Quantifying drylands' drought resistance and recovery: the importance of drought intensity, dominant life history and grazing regime.** Global Change Biology 21: 1258-1270.

Abstract. Projected global change will increase the level of land-use and environmental stressors such as drought and grazing, particularly in drylands. Still, combined effects of drought and grazing on plant production are poorly understood, thus hampering adequate projections and development of mitigation strategies. We used a large, cross-continental database consisting of 174 long-term datasets from >30 dryland regions to quantify ecosystem responses to drought and grazing with the ultimate goal to increase functional understanding in these responses. Two key aspects of ecosystem stability, resistance to and recovery after a drought, were evaluated based on standardized and normalized aboveground net primary production (ANPP) data. Drought intensity was quantified using the standardized precipitation index. We tested effects of drought intensity, grazing regime (grazed, ungrazed), biome (grassland, shrubland, savanna) or dominant life history (annual, perennial) of the herbaceous layer to assess the relative importance of these factors for ecosystem stability, and to identify predictable relationships between drought intensity and ecosystem resistance and recovery. We found that both components of ecosystem stability were better explained by dominant herbaceous life history than by biome. Increasing drought intensity (quasi-) linearly reduced ecosystem resistance. Even though annual and perennial systems showed the same response rate to increasing drought intensity, they differed in their general magnitude of resistance, with annual systems being ca. 27% less resistant. In contrast, systems with an herbaceous layer dominated by annuals had substantially higher postdrought recovery, particularly when grazed. Combined effects of drought and grazing were not merely additive but modulated by dominant life history of the herbaceous layer. To the best of our knowledge, our study established the first predictive, cross-continental model between drought intensity and drought-related relative losses in ANPP, and suggests that systems with an herbaceous layer dominated by annuals are more prone to ecosystem degradation under future global change regimes.

Fish and Wildlife

Benard, M. F. 2015. **Warmer winters reduce frog fecundity and shift breeding phenology, which consequently alters larval development and metamorphic timing.** Global Change Biology 21: 1058-1065.

Abstract. One widely documented phenological response to climate change is the earlier occurrence of spring-breeding events. While such climate change-driven shifts in phenology are common, their consequences for individuals and populations have rarely been investigated. I addressed this gap in our knowledge by using a multi-year observational study of six wood frog (*Rana sylvatica*) populations near the southern edge of their range. I tested first if winter temperature or precipitation affected the date of breeding and female fecundity, and second if timing of breeding affected subsequent larval development rate, mass at metamorphosis, date of metamorphosis, and survival. Warmer winters were associated with earlier breeding but reduced female fecundity. Winter precipitation did not affect breeding date, but was positively associated with female fecundity. There was no association between earlier breeding and larval survival or mass at metamorphosis, but earlier breeding was associated with delayed larval development. The delay in larval development was explained through a counterintuitive correlation between breeding date and temperature during larval development. Warmer winters led to earlier breeding, which in turn was associated with cooler post-breeding temperatures that slowed larval development. The delay in larval development did not fully compensate for the earlier breeding, such that for every 2 days earlier that breeding took place, the average date of metamorphosis was 1 day earlier. Other studies have found that earlier metamorphosis is associated with increased postmetamorphic growth and survival, suggesting that earlier breeding has beneficial effects on wood frog populations.

Stanton, J. C., K. T. Shoemaker, R. G. Pearson, and H. R. Akçakaya. 2015. **Warning times for species extinctions due to climate change.** Global Change Biology 21: 1066-1077.

Abstract. Climate change is likely to become an increasingly major obstacle to slowing the rate of species extinctions. Several new assessment approaches have been proposed for identifying climate-vulnerable species, based on the assumption that established systems such as the IUCN Red List need revising or replacing because they were not developed to explicitly consider climate change. However, no

assessment approach has been tested to determine its ability to provide advanced warning time for conservation action for species that might go extinct due to climate change. To test the performance of the Red List system in this capacity, we used linked niche-demographic models with habitat dynamics driven by a 'business-as-usual' climate change scenario. We generated replicate 100-year trajectories for range-restricted reptiles and amphibians endemic to the United States. For each replicate, we categorized the simulated species according to IUCN Red List criteria at annual, 5-year, and 10-year intervals (the latter representing current practice). For replicates that went extinct, we calculated warning time as the number of years the simulated species was continuously listed in a threatened category prior to extinction. To simulate data limitations, we repeated the analysis using a single criterion at a time (disregarding other listing criteria). Results show that when all criteria can be used, the Red List system would provide several decades of warning time (median = 62 years; >20 years for 99% of replicates), but suggest that conservation actions should begin as soon as a species is listed as Vulnerable, because 50% of replicates went extinct within 20 years of becoming uplisted to Critically Endangered. When only one criterion was used, warning times were substantially shorter, but more frequent assessments increased the warning time by about a decade. Overall, we found that the Red List criteria reliably provide a sensitive and precautionary way to assess extinction risk under climate change.

Invertebrates

Ma, G., V. H. W. Rudolf, and C.-S. Ma. 2015. **Extreme temperature events alter demographic rates, relative fitness, and community structure.** Global Change Biology 21: 1794-1808.

Abstract. The frequency and magnitude of extreme events are predicted to increase under future climate change. Despite recent advancements, we still lack a detailed understanding of how changes in the frequency and amplitude of extreme climate events are linked to the temporal and spatial structure of natural communities. To answer this question, we used a combination of laboratory experiments, field experiments, and analysis of multi-year field observations to reveal the effects of extreme high temperature events on the demographic rates and relative dominance of three co-occurrence aphid species which differ in their transmission efficiency of different agricultural pathogens. We then linked the geographical shift in their relative

dominance to frequent extreme high temperatures through a meta-analysis. We found that both frequency and amplitude of extreme high temperatures altered demographic rates of species. However, these effects were species-specific. Increasing the frequency and amplitude of extreme temperature events altered which species had the highest fitness. Importantly, this change in relative fitness of species was consistent with significant changes in the relative dominance of species in natural communities in a 1 year long field heating experiment and 6 year long field survey of natural populations. Finally, at a global spatial scale, we found the same relationship between relative abundance of species and frequency of extreme temperatures. Together, our results indicate that changes in frequency and amplitude of extreme high temperatures can alter the temporal and spatial structure of natural communities, and that these changes are driven by asymmetric effects of high temperatures on the demographic rates and fitness of species. They also highlight the importance of understanding how extreme events affect the life-history of species for predicting the impacts of climate change at the individual and community level, and emphasize the importance of using a broad range of approaches when studying climate change.

Marshall, K. E., and B. J. Sinclair. 2015. **The relative importance of number, duration and intensity of cold stress events in determining survival and energetics of an overwintering insect.** Functional Ecology 29: 357-366.

Abstract. 1. The relationship between abiotic stress and fitness in an individual is usually described by the intensity and duration of stress. Yet in natural systems, variability in abiotic stress is common. Since individuals have physiological and fitness responses to single bouts of stress, frequency of stress may also determine the lifetime success of an organism. However, the majority of laboratory studies have focused only on the effects of single stress events.

2. We investigated the relative importance of stress parameters including duration, intensity and number of cold events on the short-term physiology and long-term fitness in the freeze-avoiding eastern spruce budworm *Choristoneura fumiferana* (Lepidoptera: Tortricidae, Clemens).

3. We exposed overwintering 2nd-instar larvae of *C. fumiferana* to −5 °C, −10 °C, −15 °C or −20 °C, for either a single exposure of 120 h or repeated 12 h exposures (3, 6 or 10 exposures). Changes in short-term physiology were quantified by cryoprotectant content, energetic stores and supercooling point. Long-term fitness effects were

measured by rearing individuals after overwintering and recording successful eclosion as adults, development time from 2nd instar to adult, and adult size.

4. We found that long-term survival of *C. fumiferana* was most strongly affected by the number of low-temperature stress events rather than intensity or duration, despite increased investment into cryoprotection at the expense of glycogen reserves. Sublethal measures such as adult size were unaffected by low-temperature stress.

5. Thus, we show that frequency of stress is an important, yet frequently neglected, parameter in the study of the effects of abiotic stress. The responses we documented here suggest that frequency of stress may be an additional important parameter for modelling the effects of abiotic stress on populations.

Pincebourde, S., and J. Casas. 2014. **Warming tolerance across insect ontogeny: influence of joint shifts in microclimates and thermal limits.** Ecology 96:986-997.

Abstract. The impact of warming on the persistence and distribution of ectotherms is often forecasted from their warming tolerance, inferred as the difference between their upper thermal limit and macroclimate temperature. Ectotherms, however, are thermally adapted to their microclimates, which can deviate substantially from macroscale conditions. Ignoring microclimates can therefore bias estimates of warming tolerance. We compared warming tolerance of an insect across its ontogeny when calculated from macro- and microclimate temperatures. We used a heat balance model to predict experienced microclimate temperatures from macroclimate, and we measured thermal limits for several life stages. The model shows a concomitant increase in microclimate temperatures and thermal limits across insect ontogeny, despite the fact that they all share the same macroclimate. Consequently, warming tolerance, as estimated from microclimate temperature, remained constant across ontogeny. When calculated from macroclimate temperature, however, warming tolerance was overestimated by 7?10°C, depending on the life stage. Therefore, errors are expected when predicting persistence and distribution shifts of ectotherms in changing climates using macroclimate rather than microclimate.

Invasive Species

Flanagan, N. E., C. J. Richardson, and M. Ho. 2015. **Connecting differential responses of native and invasive riparian plants to climate change and environmental alteration.** Ecological Applications 25: 753-767.

Abstract. Climate change is predicted to impact river systems in the southeastern United States through alterations of temperature, patterns of precipitation and hydrology. Future climate scenarios for the southeastern United States predict (1) surface water temperatures will warm in concert with air temperature, (2) storm flows will increase and base flows will decrease, and (3) the annual pattern of synchronization between hydroperiod and water temperature will be altered. These alterations are expected to disturb floodplain plant communities, making them more vulnerable to establishment of invasive species. The primary objective of this study is to evaluate whether native and invasive riparian plant assemblages respond differently to alterations of climate and land use. To study the response of riparian wetlands to watershed and climate alterations, we utilized an existing natural experiment imbedded in gradients of temperature and hydrology found among dammed and undammed rivers. We evaluated a suite of environmental variables related to water temperature, hydrology, watershed disturbance, and edaphic conditions to identify the strongest predictors of native and invasive species abundances. We found that native species abundance is strongly influenced by climate-driven variables such as temperature and hydrology, while invasive species abundance is more strongly influenced by site-specific factors such as land use and soil nutrient availability. The patterns of synchronization between plant phenology, annual hydrographs, and annual water temperature cycles may be key factors sustaining the viability of native riparian plant communities. Our results demonstrate the need to understand the interactions between climate, land use, and nutrient management in maintaining the species diversity of riparian plant communities. Future climate change is likely to result in diminished competitiveness of native plant species, while the competitiveness of invasive species will increase due to anthropogenic watershed disturbance and accelerated nutrient and sediment export.

Soils and Hydrology

Butcher, J., D. Nover, T. Johnson, and C. Clark. 2015. **Sensitivity of lake thermal and mixing dynamics to climate change.** Climatic Change 129: 295-305.

Abstract. Warming-induced changes in lake thermal and mixing regimes present risks to water quality and ecosystem services provided by U.S. lakes and reservoirs. Modulation of responses by different physical and hydroclimatic settings are not well understood. We explore the potential effects of climate change on 27 lake “archetypes” representative of a range of lakes and reservoirs occurring throughout the U.S. Archetypes are based on different combinations of depth, surface area, and water clarity. LISSS, a one-dimensional dynamic thermal simulation model, is applied to assess lake response to multiple mid-21st century change scenarios applied to nine baseline climate series from different hydroclimatic regions of the U.S. Results show surface water temperature increases of about 77 % of increase in average air temperature change. Bottom temperature changes are less (around 30 %) for deep lakes and in regions that maintain mid-winter air temperatures below freezing. Significant decreases in length of ice cover are projected, and the extent and strength of stratification will increase throughout the U.S., with systematic differences associated with depth, surface area, and clarity. These projected responses suggest a range of future challenges that lake managers are likely to face. Changes in thermal and mixing dynamics suggest increased risk of summer hypoxic conditions and cyanobacterial blooms. Increased water temperatures above the summer thermocline could be a problem for cold water fisheries management in many lakes. Climate-induced changes in water balance and mass inputs of nutrients may further exacerbate the vulnerability of lakes to climate change.

Nielsen, U. N., and B. A. Ball. 2015. **Impacts of altered precipitation regimes on soil communities and biogeochemistry in arid and semi-arid ecosystems.** Global Change Biology 21: 1407-1421.

Abstract. Altered precipitation patterns resulting from climate change will have particularly significant consequences in water-limited ecosystems, such as arid to semi-arid ecosystems, where discontinuous inputs of water control biological processes. Given that these ecosystems cover more than a third of Earth's terrestrial surface, it is important to understand how they respond to such alterations. Altered water availability may impact both aboveground and belowground communities and the interactions between these, with potential impacts on ecosystem functioning; however, most studies to date have focused exclusively on vegetation responses to altered precipitation regimes. To synthesize our understanding of potential climate change impacts on dryland ecosystems, we present here a review of current literature that reports the effects of precipitation events and altered precipitation regimes on belowground biota and biogeochemical cycling. Increased precipitation generally increases microbial biomass and fungal:bacterial ratio. Few studies report responses to reduced precipitation but the effects likely counter those of increased precipitation. Altered precipitation regimes have also been found to alter microbial community composition but broader generalizations are difficult to make. Changes in event size and frequency influences invertebrate activity and density with cascading impacts on the soil food web, which will likely impact carbon and nutrient pools. The long-term implications for biogeochemical cycling are inconclusive but several studies suggest that increased aridity may cause decoupling of carbon and nutrient cycling. We propose a new conceptual framework that incorporates hierarchical biotic responses to individual precipitation events more explicitly, including moderation of microbial activity and biomass by invertebrate grazing, and use this framework to make some predictions on impacts of altered precipitation regimes in terms of event size and frequency as well as mean annual precipitation. While our understanding of dryland ecosystems is improving, there is still a great need for longer term in situ manipulations of precipitation regime to test our model.

Drought

Mao, Y., B. Nijssen, and D. P. Lettenmaier. 2015. **Is climate change implicated in the 2013–2014 California drought? A hydrologic perspective.** Geophysical Research Letters 42: 2805-2813.

Abstract. California has experienced severe drought in 2012–2014 (which appears to be continuing into 2015), with especially low winter precipitation and mountain snowpack in winter 2013–2014. However, the extent to which climate change is implicated in the drought, if at all, is not clear. By applying modeling and statistical approaches, we construct a historical record of California snowpack, runoff, and other hydrological variables of almost 100 years in length and use the

reconstructed records to analyze climate trends in the Sierra Nevada and their impact on extreme drought events in the historic record. We confirm a general warming trend and associated decreasing trends in spring snowpack and runoff. We find that the warming may have slightly exacerbated some extreme events (including the 2013–2014 drought and the 1976–1977 drought of record), but the effect is modest; instead, these drought events are mainly the result of variability in precipitation.

Sea Level Rise

Bordbar, M. H., T. Martin, M. Latif, and W. Park. 2015. **Effects of long-term variability on projections of twenty-first century dynamic sea level.** Nature Climate Change 5: 343-347.

Abstract. Sea-level rise is one of the most pressing aspects of anthropogenic global warming with far-reaching consequences for coastal societies. However, sea-level rise did and will strongly vary from coast to coast. Here we investigate the long-term internal variability effects on centennial projections of dynamic sea level (DSL), the local departure from the globally averaged sea level. A large ensemble of global warming integrations has been conducted with a climate model, where each realization was forced by identical CO_2 increase but started from different atmospheric and oceanic initial conditions. In large parts of the mid- and high latitudes, the ensemble spread of the projected centennial DSL trends is of the same order of magnitude as the globally averaged steric sea-level rise, suggesting that internal variability cannot be ignored when assessing twenty-first-century DSL trends. The ensemble spread is considerably reduced in the mid- to high latitudes when only the atmospheric initial conditions differ while keeping the oceanic initial state identical; indicating that centennial DSL projections are strongly dependent on ocean initial conditions.

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 variability, with an average rate of rise since 1993 of +3.2 ± 0.4 mm yr^{-1} (refs 2, 3). However, satellite-based GMSL estimates do not include an allowance for potential instrumental drifts (bias drift4, 5). 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.

Neumann, J., K. Emanuel, S. Ravela, L. Ludwig, P. Kirshen, K. Bosma, and J. Martinich. 2015. **Joint effects of storm surge and sea-level rise on US Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy.** Climatic Change 129: 337-349.

Abstract. Recent literature, the US Global Change Research Program's National Climate Assessment, and recent events, such as Hurricane Sandy, highlight the need to take better account of both storm surge and sea-level rise (SLR) in assessing coastal risks of climate change. This study combines three models—a tropical cyclone simulation model; a storm surge model; and a model for economic impact and adaptation—to estimate the joint effects of storm surge and SLR for the US coast through 2100. The model is tested using multiple SLR scenarios, including those incorporating estimates of dynamic ice-sheet melting, two global greenhouse gas (GHG) mitigation policy scenarios, and multiple general circulation model climate sensitivities. The results illustrate that a large area of coastal land and property is at risk of damage from storm surge today; that land area and economic value at risk expands over time as seas rise and as storms

become more intense; that adaptation is a cost-effective response to this risk, but residual impacts remain after adaptation measures are in place; that incorporating site-specific episodic storm surge increases national damage estimates by a factor of two relative to SLR-only estimates, with greater impact on the East and Gulf coasts; and that mitigation of GHGs contributes to significant lessening of damages. For a mid-range climate-sensitivity scenario that incorporates dynamic ice sheet melting, the approach yields national estimates of the impacts of storm surge and SLR of $990 billion through 2100 (net of adaptation, cumulative undiscounted 2005$); GHG mitigation policy reduces the impacts of the mid-range climate-sensitivity estimates by $84 to $100 billion.

Adaptation

Anderson, S. C., J. W. Moore, M. M. McClure, N. K. Dulvy, and A. B. Cooper. 2015. **Portfolio conservation of metapopulations under climate change.** Ecological Applications 25: 559-572.

Abstract. Climate change is likely to lead to increasing population variability and extinction risk. Theoretically, greater population diversity should buffer against rising climate variability, and this theory is often invoked as a reason for greater conservation. However, this has rarely been quantified. Here we show how a portfolio approach to managing population diversity can inform metapopulation conservation priorities in a changing world. We develop a salmon metapopulation model in which productivity is driven by spatially distributed thermal tolerance and patterns of short- and long-term climate change. We then implement spatial conservation scenarios that control population carrying capacities and evaluate the metapopulation portfolios as a financial manager might: along axes of conservation risk and return. We show that preserving a diversity of thermal tolerances minimizes risk, given environmental stochasticity, and ensures persistence, given long-term environmental change. When the thermal tolerances of populations are unknown, doubling the number of populations conserved may nearly halve expected metapopulation variability. However, this reduction in variability can come at the expense of long-term persistence if climate change increasingly restricts available habitat, forcing ecological managers to balance society's desire for short-term stability and long-term viability. Our findings suggest the importance of conserving the processes that promote thermal-tolerance diversity, such as genetic diversity, habitat heterogeneity, and natural disturbance regimes, and demonstrate that diverse natural portfolios may be critical for metapopulation conservation in the face of increasing climate variability and change.

Becknell, J. M., A. R. Desai, M. C. Dietze, C. A. Schultz, G. Starr, P. A. Duffy, J. F. Franklin, A. Pourmokhtarian, J. Hall, P. C. Stoy, M. W. Binford, L. R. Boring, and C. L. Staudhammer. 2015. **Assessing interactions among changing climate, management, and disturbance in forests: a macrosystems approach.** BioScience 65: 263-274.

Abstract. Forests are experiencing simultaneous changes in climate, disturbance regimes, and management, all of which affect ecosystem function. Climate change is shifting ranges and altering forest productivity. Disturbance regimes are changing with the potential for novel interactions among disturbance types. In some areas, forest management practices are intensifying, whereas in other areas, lower-impact ecological methods are being used. Interactions among these changing factors are likely to alter ecosystem structure and function at regional to continental scales. A macrosystems approach is essential to assessing the broadscale impacts of these changes and quantify cross-scale interactions, emergent patterns, and feedbacks. A promising line of analysis is the assimilation of data with ecosystem models to scale processes to the macrosystem and generate projections based on alternative scenarios. Analyses of these projections can characterize the range of future variability in forest function and provide information to guide policy, industry, and science in a changing world.

Chornesky, E. A., D. D. Ackerly, P. Beier, F. W. Davis, L. E. Flint, J. J. Lawler, P. B. Moyle, M. A. Moritz, M. Scoonover, K. Byrd, P. Alvarez, N. E. Heller, E. R. Micheli, and S. B. Weiss. 2015. **Adapting California's ecosystems to a changing climate.** BioScience 65: 247-262.

Abstract. Significant efforts are underway to translate improved understanding of how climate change is altering ecosystems into practical actions for sustaining ecosystem functions and benefits. We explore this transition in California, where adaptation and mitigation are advancing relatively rapidly, through four case studies that span large spatial domains and encompass diverse ecological systems, institutions, ownerships, and policies. The case studies demonstrate the context specificity of societal efforts to adapt ecosystems to climate change and involve applications of diverse scientific tools (e.g.,

scenario analyses, downscaled climate projections, ecological and connectivity models) tailored to specific planning and management situations (alternative energy siting, wetland management, rangeland management, open space planning). They illustrate how existing institutional and policy frameworks provide numerous opportunities to advance adaptation related to ecosystems and suggest that progress is likely to be greatest when scientific knowledge is integrated into collective planning and when supportive policies and financing enable action.

Mitigation

Heller, N. E., J. Kreitler, D. D. Ackerly, S. B. Weiss, A. Recinos, R. Branciforte, L. E. Flint, A. L. Flint, and E. Micheli. 2015. **Targeting climate diversity in conservation planning to build resilience to climate change.** Ecosphere 6: art65.

Abstract. Climate change is raising challenging concerns for systematic conservation planning. Are methods based on the current spatial patterns of biodiversity effective given long-term climate change? Some conservation scientists argue that planning should focus on protecting the abiotic diversity in the landscape, which drives patterns of biological diversity, rather than focusing on the distribution of focal species, which shift in response to climate change. Climate is one important abiotic driver of biodiversity patterns, as different climates host different biological communities and genetic pools. We propose conservation networks that capture the full range of climatic diversity in a region will improve the resilience of biotic communities to climate change compared to networks that do not. In this study we used historical and future hydro-climate projections from the high resolution Basin Characterization Model to explore the utility of directly targeting climatic diversity in planning. Using the spatial planning tool, Marxan, we designed conservation networks to capture the diversity of climate types, at the regional and sub-regional scale, and compared them to networks we designed to capture the diversity of vegetation types. By focusing on the Conservation Lands Network (CLN) of the San Francisco Bay Area as a real-world case study, we compared the potential resilience of networks by examining two factors: the range of climate space captured, and climatic stability to 18 future climates, reflecting different emission scenarios and global climate models. We found that the climate-based network planned at the sub-regional scale captured a greater range of climate space and showed higher climatic stability than the vegetation and regional based-networks. At the same time, differences among network scenarios are small relative to the variance in climate stability across global climate models. Across different projected futures, topographically heterogeneous areas consistently show greater climate stability than homogenous areas. The analysis suggests that utilizing high-resolution climate and hydrological data in conservation planning improves the likely resilience of biodiversity to climate change. We used these analyses to suggest new conservation priorities for the San Francisco Bay Area.

Keppel, G., K. Mokany, G. W. Wardell-Johnson, B. L. Phillips, J. A. Welbergen, and A. E. Reside. 2015. **The capacity of refugia for conservation planning under climate change.** Frontiers in Ecology and the Environment 13: 106-112.

Abstract. Refugia – areas that may facilitate the persistence of species during large-scale, long-term climatic change –are increasingly important for conservation planning. There are many methods for identifying refugia, but the ability to quantify their potential for facilitating species persistence (ie their “capacity”) remains elusive. We propose a flexible framework for prioritizing future refugia, based on their capacity. This framework can be applied through various modeling approaches and consists of three steps: (1) definition of scope, scale, and resolution; (2) identification and quantification; and (3) prioritization for conservation. Capacity is quantified by multiple indicators, including environmental stability, microclimatic heterogeneity, size, and accessibility of the refugium. Using an integrated, semi-mechanistic modeling technique, we illustrate how this approach can be implemented to identify refugia for the plant diversity of Tasmania, Australia. The highest-capacity climate-change refugia were found primarily in cool, wet, and topographically complex environments, several of which we identify as high priorities for biodiversity conservation and management.

Ryals, R., M. D. Hartman, W. J. Parton, M. S. DeLonge, and W. L. Silver. 2015. **Long-term climate change mitigation potential with organic matter management on grasslands.** Ecological Applications 25: 531-545.

Abstract. Compost amendments to grasslands have been proposed as a strategy to mitigate climate change through carbon (C) sequestration, yet little research exists exploring the net mitigation potential or the long-term impacts of this strategy. We used field data

and the DAYCENT biogeochemical model to investigate the climate change mitigation potential of compost amendments to grasslands in California, USA. The model was used to test ecosystem C and greenhouse gas responses to a range of compost qualities (carbon to nitrogen [C:N] ratios of 11.1, 20, or 30) and application rates (single addition of 14 Mg C/ha or 10 annual additions of 1.4 Mg $C{\cdot}ha^{-1}{\cdot}yr^{-1}$). The model was parameterized using site-specific weather, vegetation, and edaphic characteristics and was validated by comparing simulated soil C, nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) fluxes, and net primary production (NPP) with three years of field data. All compost amendment scenarios led to net greenhouse gas sinks that persisted for several decades. Rates of climate change mitigation potential ranged from 130 ± 3 g to 158 ± 8 g $CO2\text{-}eq{\cdot}m^{-2}{\cdot}yr^{-1}$ (where "eq" stands for "equivalents") when assessed over a 10-year time period and 63 ± 2 g to 84 ± 10 g $CO2\text{-}eq{\cdot}m^{-2}{\cdot}yr^{-1}$ over a 30-year time period. Both C storage and greenhouse gas emissions increased rapidly following amendments. Compost amendments with lower C:N led to higher C sequestration rates over time. However, these soils also experienced greater N_2O fluxes. Multiple smaller compost additions resulted in similar cumulative C sequestration rates, albeit with a time lag, and lower cumulative N_2O emissions. These results identify a trade-off between maximizing C sequestration and minimizing N_2O emissions following amendments, and suggest that compost additions to grassland soils can have a long-term impact on C and greenhouse gas dynamics that contributes to climate change mitigation.

Stephens, S. L., J. M. Lydersen, B. M. Collins, D. L. Fry, and M. D. Meyer. 2015. **Historical and current landscape-scale ponderosa pine and mixed conifer forest structure in the Southern Sierra Nevada.** Ecosphere 6: art79.

Abstract. Many managers today are tasked with restoring forests to mitigate the potential for uncharacteristically severe fire. One challenge to this mandate is the lack of large-scale reference information on forest structure prior to impacts from Euro-American settlement. We used a robust 1911 historical dataset that covers a large geographic extent (>10,000 ha) and has unbiased sampling locations to compare past and current forest conditions for ponderosa pine and mixed conifer forests in the southern Sierra Nevada. The 1911 dataset contained records from 18,052 trees in 378 sampled transects, totaling just over 300 ha in transect area. Forest structure was highly variable in 1911 and shrubs were found in 54% of transects. Total tree basal area ranged from 1 to 60 m^2 ha^{-1} and tree

density from 2 to 170 ha^{-1} (based on trees >30 cm dbh). K-means cluster analysis divided transects into four groups: mixed conifer-high basal area (MC High BA), mixed conifer-average basal area (MC Ave BA), mixed conifer-average basal area-high shrubs (MC Ave BA Shrubs), and ponderosa pine (Pond Pine). The percentage of this 1911 landscape that experienced high severity fire was low and varied from 1-3% in mixed conifer forests and 4-6% in ponderosa pine forests. Comparing forest inventory data from 1911 to the present indicates that current forests have changed drastically, particularly in tree density, canopy cover, the density of large trees, dominance of white fir in mixed conifer forests, and the similarity of tree basal area in contemporary ponderosa pine and mixed conifer forests. Average forest canopy cover increased from 25-49% in mixed conifer forests, and from 12-49% in ponderosa pine forests from 1911 to the present; canopy cover in current forest types is similar but in 1911 mixed conifer forests had twice the canopy cover as ponderosa pine forests. Current forest restoration goals in the southern Sierra Nevada are often skewed toward the higher range of these historical values, which will limit the effectiveness of these treatments if the objective is to produce resilient forest ecosystems into the future.