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

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Oregon-Washington BLM employees can access some of the papers listed below through the OSO Science Info SharePoint site at: http://teamspace/or/sites/ScienceInfo/Pages/ClimateChange.aspx.

Climate

Latif, M., V. Semenov, and W. Park. 2015. **Super El Niños in response to global warming in a climate model.** Climatic Change 132: 489-500.

Abstract. Extraordinarily strong El Niño events, such as those of 1982/1983 and 1997/1998, cause havoc with weather around the world, adversely influence terrestrial and marine ecosystems in a number of regions and have major socio-economic impacts. Here we show by means of climate model integrations that El Niño events may be boosted by global warming. An important factor causing El Niño intensification is warming of the western Pacific warm pool, which strongly enhances surface zonal wind sensitivity to eastern equatorial Pacific sea surface temperature anomalies. This in conjunction with larger and more zonally asymmetric equatorial Pacific upper ocean heat content supports stronger and longer lasting El Niños. The most intense events, termed Super El Niños, drive extraordinary global teleconnections which are associated with exceptional surface air temperature and rainfall anomalies over many land areas.

Lehmann, J., D. Coumou, and K. Frieler. 2015. **Increased record-breaking precipitation events under global warming.** Climatic Change 132: 501-515.

Abstract. In the last decade record-breaking rainfall events have occurred in many places around the world causing severe impacts to human society and the environment including agricultural losses and floodings. There is now medium confidence that human-induced greenhouse gases have contributed to changes in heavy precipitation events at the global scale. Here, we present the first analysis of record-breaking daily rainfall events using observational data. We show that over the last three decades the number of record-breaking

events has significantly increased in the global mean. Globally, this increase has led to 12 % more record-breaking rainfall events over 1981–2010 compared to those expected in stationary time series. The number of record-breaking rainfall events peaked in 2010 with an estimated 26 % chance that a new rainfall record is due to long-term climate change. This increase in record-breaking rainfall is explained by a statistical model which accounts for the warming of air and associated increasing water holding capacity only. Our results suggest that whilst the number of rainfall record-breaking events can be related to natural multi-decadal variability over the period from 1901 to 1980, observed record-breaking rainfall events significantly increased afterwards consistent with rising temperatures.

Mazdiyasni, O., and A. AghaKouchak. 2015. **Substantial increase in concurrent droughts and heatwaves in the United States.** Proceedings of the National Academy of Sciences 112: 11484-11489.

Abstract. A combination of climate events (e.g., low precipitation and high temperatures) may cause a significant impact on the ecosystem and society, although individual events involved may not be severe extremes themselves. Analyzing historical changes in concurrent climate extremes is critical to preparing for and mitigating the negative effects of climatic change and variability. This study focuses on the changes in concurrences of heatwaves and meteorological droughts from 1960 to 2010. Despite an apparent hiatus in rising temperature and no significant trend in droughts, we show a substantial increase in concurrent droughts and heatwaves across most parts of the United States, and a statistically significant shift in the distribution of concurrent extremes. Although commonly used trend analysis methods do not show any trend in concurrent droughts and heatwaves, a unique statistical approach discussed in this study exhibits a statistically significant change in the distribution of the data.

Otto, F. L., C. T. Ferro, T. Fricker, and E. Suckling. 2015. **On judging the credibility of climate predictions.** Climatic Change 132: 47-60.

Abstract. Incorporating a prediction into future planning and decision making is advisable only if we have judged the prediction’s credibility. This is notoriously difficult and controversial in the case of predictions of future climate. By reviewing epistemic arguments about climate model performance, we discuss how to make and justify judgments

about the credibility of climate predictions. We propose a new bounding argument that justifies basing such judgments on the past performance of possibly dissimilar prediction problems. This encourages a more explicit use of data in making quantitative judgments about the credibility of future climate predictions, and in training users of climate predictions to become better judges of credibility. We illustrate the approach using decadal predictions of annual mean, global mean surface air temperature.

Rajaratnam, B., J. Romano, M. Tsiang, and N. S. Diffenbaugh. 2015. **Debunking the climate hiatus.** Climatic Change 133: 129-140.

Abstract. The reported "hiatus" in the warming of the global climate system during this century has been the subject of intense scientific and public debate, with implications ranging from scientific understanding of the global climate sensitivity to the rate in which greenhouse gas emissions would need to be curbed in order to meet the United Nations global warming target. A number of scientific hypotheses have been put forward to explain the hiatus, including both physical climate processes and data artifacts. However, despite the intense focus on the hiatus in both the scientific and public arenas, rigorous statistical assessment of the uniqueness of the recent temperature time-series within the context of the long-term record has been limited. We apply a rigorous, comprehensive statistical analysis of global temperature data that goes beyond simple linear models to account for temporal dependence and selection effects. We use this framework to test whether the recent period has demonstrated i) a hiatus in the trend in global temperatures, ii) a temperature trend that is statistically distinct from trends prior to the hiatus period, iii) a "stalling" of the global mean temperature, and iv) a change in the distribution of the year-to-year temperature increases. We find compelling evidence that recent claims of a "hiatus" in global warming lack sound scientific basis. Our analysis reveals that there is no hiatus in the increase in the global mean temperature, no statistically significant difference in trends, no stalling of the global mean temperature, and no change in year-to-year temperature increases.

Wu, S.-Y. 2015. **Changing characteristics of precipitation for the contiguous United States.** Climatic Change 132: 677-692.

Abstract. Using the US collection from the Global Historical Climatology Network Daily (GHCN-D) precipitation data for the contiguous United States (CONUS), this study examines the changing characteristics of precipitation during 1951–2013. In addition to mean precipitation, all precipitation events are divided into three categories: light, moderate, and heavy based on percentile thresholds. The historical trends are established for precipitation total, frequency and intensity, as well as for total and frequency of different intensity categories. Results show that from 1951 to 2013, mean precipitation increased at 1.66 % per decade, a higher rate than previous estimates. About one third of the increase is attributed to frequency change, whereas the other two thirds are attributed to an intensity increase. There was a slight decrease in light precipitation, a small increase in moderate precipitation, and much higher increase for heavy precipitation. Spatially, eastern and northern parts of the CONUS experienced higher rates of increase, whereas western regions experienced less increase. A statistically significant positive correlation exists between mean precipitation and precipitation change, suggesting the wet regions experienced more precipitation increase than dry regions. Seasonally, precipitation increased most for the fall, less in other seasons. Particularly, there were significant decreasing trends in summer precipitation for many parts of western and central CONUS. Regional frequency analysis is used to examine the change in extreme precipitation events with return intervals longer than a year. Results show that extreme precipitation events increased for most of the CONUS with the exception of the west region. These changes were a result of both a shift in the mean state and the shape of the precipitation data distribution.

Carbon and Carbon Storage

Buma, B., and T. M. Barrett. 2015. **Spatial and topographic trends in forest expansion and biomass change, from regional to local scales.** Global Change Biology 21: 3445-3454.

Abstract. Natural forest growth and expansion are important carbon sequestration processes globally. Climate change is likely to increase forest growth in some regions via CO_2 fertilization, increased temperatures, and altered precipitation; however, altered disturbance regimes and climate stress (e.g. drought) will act to reduce carbon stocks in forests as well. Observations of asynchrony in forest change is useful in determining current trends in forest carbon stocks, both in terms of forest density (e.g. Mg ha^{-1}) and spatially (extent and location). Monitoring change in natural (unmanaged) areas is

particularly useful, as while afforestation and recovery from historic land use are currently large carbon sinks, the long-term viability of those sinks depends on climate change and disturbance dynamics at their particular location. We utilize a large, unmanaged biome (>135,000 km^2) which spans a broad latitudinal gradient to explore how variation in location affects forest density and spatial patterning: the forests of the North American temperate rainforests in Alaska, which store >2.8 Pg C in biomass and soil, equivalent to >8% of the C in contiguous US forests. We demonstrate that the regional biome is shifting; gains exceed losses and are located in different spatio-topographic contexts. Forest gains are concentrated on northerly aspects, lower elevations, and higher latitudes, especially in sheltered areas, whereas loss is skewed toward southerly aspects and lower latitudes. Repeat plot-scale biomass data (n = 759) indicate that within-forest biomass gains outpace losses (live trees >12.7 cm diameter, 986 Gg yr^{-1}) on gentler slopes and in higher latitudes. This work demonstrates that while temperate rainforest dynamics occur at fine spatial scales (<1000 m^2), the net result of thousands of individual events is regionally patterned change. Correlations between the disturbance/establishment imbalance and biomass accumulation suggest the potential for relatively rapid biome shifts and biomass changes.

Chen, L., P. Smith, and Y. Yang. 2015. **How has soil carbon stock changed over recent decades?** Global Change Biology 21: 3197-3199.

First Paragraph. Soil is the largest stock of carbon (C) in the terrestrial biosphere, so even slight changes in soil C stock may induce significant fluctuations in the atmospheric C dioxide (CO_2) concentration. Early coupled C-climate models predicted that positive C-climate feedback would be triggered due to the acceleration of C release to the atmosphere under future climate warming (Cox et al., 2000). However, due to the omission of key microbial components and biogeochemical mechanisms in these models (Wieder et al., 2013), these predictions remain controversial, because soil C dynamics is still highly uncertain among results simulated by 11 Earth system models (ESMs) involved in CMIP5 (Ciais et al., 2013). Likewise, experimental evidence is also contradictory, revealing increasing, decreasing, or nonsignificant changes among individual experiments (Lu et al., 2013). Given the very mixed results from both modelling and experimental studies, we present a global synthesis of soil C changes to evaluate a central tendency.

Cousins, S. J. M., J. J. Battles, J. E. Sanders, and R. A. York. 2015. **Decay patterns and carbon density of standing dead trees in California mixed conifer forests.** Forest Ecology and Management 353: 136-147.

Abstract. Dead wood plays important structural and biogeochemical roles in forest ecosystem processes. Some aspects of woody debris dynamics have been carefully studied, but the decay patterns and carbon density of standing dead (SD) trees are only weakly characterized. Climbing forest mortality rates are also driving increases in the creation and abundance of SD trees. All forms of forest carbon accounting, from stand-level biomass calculations to dynamic earth systems models, are improved by a better understanding of SD tree physical and chemical traits. Using dimensional analysis, we described the patterns of density, carbon concentration, and net carbon density in decaying SD trees of six California mixed conifer species. As decay class advanced, trees showed a progressively lower density and a small increase in carbon concentration. Net carbon density of the most decayed SD trees was only 60% that of live trees. The key characteristics of SD trees that determine these patterns are species, surface to volume ratio, and relative position within the tree. The decay of SD trees and how deadwood biomass is estimated in large scale inventories also have repercussions in greenhouse gas accounting. When the measured changes in carbon density are applied to SD carbon stock estimates for California mixed conifer forests, the decay-adjusted estimates are 3.66–3.74 Tg (18%) lower than estimates that do not incorporate change due to decay.

Noormets, A., D. Epron, J. C. Domec, S. G. McNulty, T. Fox, G. Sun, and J. S. King. 2015. **Effects of forest management on productivity and carbon sequestration: A review and hypothesis.** Forest Ecology and Management 355: 124-140.

Abstract. With an increasing fraction of the world’s forests being intensively managed for meeting humanity’s need for wood, fiber and ecosystem services, quantitative understanding of the functional changes in these ecosystems in comparison with natural forests is needed. In particular, the role of managed forests as long-term carbon (C) sinks and for mitigating climate change require a detailed assessment of their carbon cycle on different temporal scales. In the current review we assess available data on the structure and function of the world’s forests, explore the main differences in the C exchange

between managed and unmanaged stands, and explore potential physiological mechanisms behind both observed and expected changes. Two global databases that include classification for management indicate that managed forests are about 50 years younger, include 25% more coniferous stands, and have about 50% lower C stocks than unmanaged forests. The gross primary productivity (GPP) and total net primary productivity (NPP) are the similar, but relatively more of the assimilated carbon is allocated to aboveground pools in managed than in unmanaged forests, whereas allocation to fine roots and rhizosymbionts is lower. This shift in allocation patterns is promoted by increasing plant size, and by increased nutrient availability. Long-term carbon sequestration potential in soils is assessed through the ratio of heterotrophic respiration to total detritus production, which indicates that (i) the forest soils may be losing more carbon on an annual basis than they regain in detritus, and (ii) the deficit appears to be greater in managed forests. While climate change and management factors (esp. fertilization) both contribute to greater carbon accumulation potential in the soil, the harvest-related increase in decomposition affects the C budget over the entire harvest cycle. Although the findings do not preclude the use of forests for climate mitigation, maximizing merchantable productivity may have significant carbon costs for the soil pool. We conclude that optimal management strategies for maximizing multiple benefits from ecosystem services require better understanding of the dynamics of belowground allocation, carbohydrate availability, heterotrophic respiration, and carbon stabilization in the soil.

Russell, M. B., G. M. Domke, C. W. Woodall, and A. W. D’Amato. 2015. **Comparisons of allometric and climate-derived estimates of tree coarse root carbon stock in forests of the United States.** Carbon Balance and Management 10: 20. Doi: 10.1186/s13021-015-0032-7

Abstract. Background. Refined estimation of carbon (C) stocks within forest ecosystems is a critical component of efforts to reduce greenhouse gas emissions and mitigate the effects of projected climate change through forest C management. Specifically, belowground C stocks are currently estimated in the United States’ national greenhouse gas inventory (US NGHGI) using nationally consistent species- and diameter-specific equations applied to individual trees. Recent scientific evidence has pointed to the importance of climate as a driver of belowground C stocks. This study estimates belowground C using current methods applied in the US NGHGI and describes a new

approach for merging both allometric models with climate-derived predictions of belowground C stocks.

Results. Climate-adjusted predictions were variable depending on the region and forest type of interest, but represented an increase of 368.87 Tg of belowground C across the US, or a 6.4 % increase when compared to currently-implemented NGHGI estimates. Random forests regressions indicated that aboveground biomass, stand age, and stand origin (i.e., planted versus artificial regeneration) were useful predictors of belowground C stocks. Decreases in belowground C stocks were modeled after projecting mean annual temperatures at various locations throughout the US up to year 2090.

Conclusions. By combining allometric equations with trends in temperature, we conclude that climate variables can be used to adjust the US NGHGI estimates of belowground C stocks. Such strategies can be used to determine the effects of future global change scenarios within a C accounting framework.

Tan, Z., S. Liu, T. L. Sohl, Y. Wu, and C. J. Young. 2015. **Ecosystem carbon stocks and sequestration potential of federal lands across the conterminous United States.** Proceedings of the National Academy of Sciences 112: 12723-12728.

Abstract. Federal lands across the conterminous United States (CONUS) account for 23.5% of the CONUS terrestrial area but have received no systematic studies on their ecosystem carbon (C) dynamics and contribution to the national C budgets. The methodology for US Congress-mandated national biological C sequestration potential assessment was used to evaluate ecosystem C dynamics in CONUS federal lands at present and in the future under three Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) A1B, A2, and B1. The total ecosystem C stock was estimated as 11,613 Tg C in 2005 and projected to be 13,965 Tg C in 2050, an average increase of 19.4% from the baseline. The projected annual C sequestration rate (in kilograms of carbon per hectare per year) from 2006 to 2050 would be sinks of 620 and 228 for forests and grasslands, respectively, and C sources of 13 for shrublands. The federal lands' contribution to the national ecosystem C budget could decrease from 23.3% in 2005 to 20.8% in 2050. The C sequestration potential in the future depends not only on the footprint of individual ecosystems but also on each federal agency's land use and management. The results presented here update our current knowledge about the baseline ecosystem C stock and sequestration potential of federal lands, which would be useful for federal agencies to

decide management practices to achieve the national greenhouse gas (GHG) mitigation goal.

Wiechmann, M., M. Hurteau, M. North, G. Koch, and L. Jerabkova. 2015. **The carbon balance of reducing wildfire risk and restoring process: an analysis of 10-year post-treatment carbon dynamics in a mixed-conifer forest.** Climatic Change 132: 709-719.

Abstract. Forests sequester carbon from the atmosphere, helping mitigate climate change. In fire-prone forests, burn events result in direct and indirect emissions of carbon. High fire-induced tree mortality can cause a transition from a carbon sink to source, but thinning and prescribed burning can reduce fire severity and carbon loss when wildfire occurs. However, treatment implementation requires carbon removal and emissions to reduce high-severity fire risk. The carbon removed and emitted during treatment may be resequestered by subsequent tree growth, although there is much uncertainty regarding the length of time required. To assess the long-term carbon dynamics of thinning and burning treatments, we quantified the 10-year post-treatment carbon stocks and 10-year net biome productivity (NBP) from a full-factorial experiment involving three levels of thinning and two levels of burning in a mixed-conifer forest in California's Sierra Nevada. Our results indicate that (1) the understory thin treatment, that retained large trees, quickly recovered the initial carbon emissions (NBP = 31.4 ± 4.2 Mg C ha^{-1}), (2) the carbon emitted from prescribed fire in the burn-only treatment was resequestered within the historical fire return interval (NBP = 32.8 ± 3.5 Mg C ha^{-1}), and (3) the most effective treatment for reducing fire risk, understory thin and burn, had negative NBP (−6.0 ± 4.5 Mg C ha^{-1}) because of post-fire large tree mortality. Understory thinning and prescribed burning can help stabilize forest carbon and restore ecosystem resilience, but this requires additional emissions beyond only thinning or only burning. Retaining additional mid-sized trees may reduce the carbon impacts of understory thinning and burning.

Phenology Changes

Fu, Y. H., H. Zhao, S. Piao, M. Peaucelle, S. Peng, G. Zhou, P. Ciais, M. Huang, A. Menzel, J. Penuelas, Y. Song, Y. Vitasse, Z. Zeng, and I. A. Janssens. 2015. **Declining global warming effects on the phenology of spring leaf unfolding.** Nature 526: 104-107.

Abstract. Earlier spring leaf unfolding is a frequently observed response of plants to climate warming. Many deciduous tree species require chilling for dormancy release, and warming-related reductions in chilling may counteract the advance of leaf unfolding in response to warming. Empirical evidence for this, however, is limited to saplings or twigs in climate-controlled chambers. Using long-term in situ observations of leaf unfolding for seven dominant European tree species at 1,245 sites, here we show that the apparent response of leaf unfolding to climate warming (S_T, expressed in days advance of leaf unfolding per °C warming) has significantly decreased from 1980 to 2013 in all monitored tree species. Averaged across all species and sites, S_T decreased by 40% from 4.0 ± 1.8 days °C^{-1} during 1980–1994 to 2.3 ± 1.6 days °C^{-1} during 1999–2013. The declining S_T was also simulated by chilling-based phenology models, albeit with a weaker decline (24–30%) than observed in situ. The reduction in ST is likely to be partly attributable to reduced chilling. Nonetheless, other mechanisms may also have a role, such as ‘photoperiod limitation’ mechanisms that may become ultimately limiting when leaf unfolding dates occur too early in the season. Our results provide empirical evidence for a declining S_T, but also suggest that the predicted strong winter warming in the future may further reduce S_T and therefore result in a slowdown in the advance of tree spring phenology.

Forest Vegetation

Bansal, S., J. B. St. Clair, C. A. Harrington, and P. J. Gould. 2015. **Impact of climate change on cold hardiness of Douglas-fir (*Pseudotsuga menziesii*): environmental and genetic considerations.** Global Change Biology 21: 3814-3826.

Abstract. The success of conifers over much of the world's terrestrial surface is largely attributable to their tolerance to cold stress (i.e., cold hardiness). Due to an increase in climate variability, climate change may reduce conifer cold hardiness, which in turn could impact ecosystem functioning and productivity in conifer-dominated forests.

The expression of cold hardiness is a product of environmental cues (E), genetic differentiation (G), and their interaction (G × E), although few studies have considered all components together. To better understand and manage for the impacts of climate change on conifer cold hardiness, we conducted a common garden experiment replicated in three test environments (cool, moderate, and warm) using 35 populations of coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) to test the hypotheses: (i) cool-temperature cues in fall are necessary to trigger cold hardening, (ii) there is large genetic variation among populations in cold hardiness that can be predicted from seed-source climate variables, (iii) observed differences among populations in cold hardiness in situ are dependent on effective environmental cues, and (iv) movement of seed sources from warmer to cooler climates will increase risk to cold injury. During fall 2012, we visually assessed cold damage of bud, needle, and stem tissues following artificial freeze tests. Cool-temperature cues (e.g., degree hours below 2 °C) at the test sites were associated with cold hardening, which were minimal at the moderate test site owing to mild fall temperatures. Populations differed 3-fold in cold hardiness, with winter minimum temperatures and fall frost dates as strong seed-source climate predictors of cold hardiness, and with summer temperatures and aridity as secondary predictors. Seed-source movement resulted in only modest increases in cold damage. Our findings indicate that increased fall temperatures delay cold hardening, warmer/drier summers confer a degree of cold hardiness, and seed-source movement from warmer to cooler climates may be a viable option for adapting coniferous forest to future climate.

Fensham, R. J., J. Fraser, H. J. MacDermott, and J. Firn. 2015. **Dominant tree species are at risk from exaggerated drought under climate change**. Global Change Biology 21: 3777-3785.

Abstract. Predicting the consequences of climate change on forest systems is difficult because trees may display species-specific responses to exaggerated droughts that may not be reflected by the climatic envelope of their geographic range. Furthermore, few studies have examined the postdrought recovery potential of drought-susceptible tree species. This study develops a robust ranking of the drought susceptibility of 21 tree species based on their mortality after two droughts (1990s and 2000s) in the savanna of north-eastern Australia. Drought-induced mortality was positively related to species dominance, negatively related to the ratio of postdrought seedlings to adults and had no relationship to the magnitude of extreme drought within the species current geographic ranges. These results suggest

that predicting the consequences of exaggerated drought on species' geographic ranges is difficult, but that dominant species like Eucalyptus with relatively slow rates of population recovery and dispersal are the most susceptible. The implications for savanna ecosystems are lower tree densities and basal area.

Fernández, M., H. H. Hamilton, and L. M. Kueppers. 2015. **Back to the future: using historical climate variation to project near-term shifts in habitat suitable for coast redwood.** Global Change Biology 21: 4141-4152.

Abstract. Studies that model the effect of climate change on terrestrial ecosystems often use climate projections from downscaled global climate models (GCMs). These simulations are generally too coarse to capture patterns of fine-scale climate variation, such as the sharp coastal energy and moisture gradients associated with wind-driven upwelling of cold water. Coastal upwelling may limit future increases in coastal temperatures, compromising GCMs' ability to provide realistic scenarios of future climate in these coastal ecosystems. Taking advantage of naturally occurring variability in the high-resolution historic climatic record, we developed multiple fine-scale scenarios of California climate that maintain coherent relationships between regional climate and coastal upwelling. We compared these scenarios against coarse resolution GCM projections at a regional scale to evaluate their temporal equivalency. We used these historically based scenarios to estimate potential suitable habitat for coast redwood (Sequoia sempervirens D. Don) under 'normal' combinations of temperature and precipitation, and under anomalous combinations representative of potential future climates. We found that a scenario of warmer temperature with historically normal precipitation is equivalent to climate projected by GCMs for California by 2020–2030 and that under these conditions, climatically suitable habitat for coast redwood significantly contracts at the southern end of its current range. Our results suggest that historical climate data provide a high-resolution alternative to downscaled GCM outputs for near-term ecological forecasts. This method may be particularly useful in other regions where local climate is strongly influenced by ocean–atmosphere dynamics that are not represented by coarse-scale GCMs.

Law, B. E., and R. H. Waring. 2015. **Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests.** Forest Ecology and Management 355: 4-14.

Abstract. Climate change has already begun to impact the structure and function of forest ecosystems in the Pacific Northwest by altering the frequency, intensity, and duration of droughts and heat stress, with implications for widespread environmental and socio-economic change. A major realization is that accumulated physiological stress can ultimately lead to tree mortality and changes in species distributions, particularly in areas away from maritime influences. To ameliorate the effects of drought, insect outbreaks, and reduce the risk of crown fires, various strategies are being tested. To make some of these strategies economical, biomass is proposed as an alternative energy source. At the same time that an increase in harvesting is being considered, there is a desire to increase carbon sequestration by forests to offset, at least in part, greenhouse gas emissions. Assessments are needed to determine current and future impacts of climate change, and to evaluate management options while considering carbon storage benefits and sustainability of ecosystem structure and function. Here we provide an overview of research results from the Pacific Northwest region where forests dominate the landscape and contain among the highest biomass on earth. In this review, we present findings that challenge common assumptions, and suggest a way to predict outcomes of changes in climate and land management in the future. The approach includes the use of observation-driven land system models that integrate the extent that forests are vulnerable to climate change, management practices, and economic considerations. It also requires increased emphasis on in situ and remotely sensed observations and experiments to initialize and test the model, and to track trends in forest condition.

Rother, M. T., T. T. Veblen, and L. G. Furman. 2015. **A field experiment informs expected patterns of conifer regeneration after disturbance under changing climate conditions.** Canadian Journal of Forest Research 45: 1607-1616.

Abstract. Climate change may inhibit tree regeneration following disturbances such as wildfire, altering post-disturbance vegetation trajectories. We implemented a field experiment to examine the effects of manipulations of temperature and water on ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) and Douglas-fir

(*Pseudotsuga menziesii* (Mirb.) Franco) seedlings planted in a low-elevation, recently disturbed setting of the Colorado Front Range. We implemented four treatments: warmed only (Wm), watered only (Wt), warmed and watered (WmWt), and control (Co). We found that measures of growth and survival varied significantly by treatment type. Average growth and survival was highest in the Wt plots, followed by the Co, WmWt, and Wm plots, respectively. This general trend was observed for both conifer species, although average growth and survival was generally higher in ponderosa pine than in Douglas-fir. Our findings suggest that warming temperatures and associated drought are likely to inhibit post-disturbance regeneration of ponderosa pine and Douglas-fir in low-elevation forests of the Colorado Front Range and that future vegetation composition and structure may differ notably from historic patterns in some areas. Our findings are relevant to other forested ecosystems in which a warming climate may similarly inhibit regeneration by dominant tree species.

Stevens, J. T., H. D. Safford, S. Harrison, and A. M. Latimer. 2015. **Forest disturbance accelerates thermophilization of understory plant communities.** Journal of Ecology 103: 1253-1263.

Abstract. Climate change is likely to shift plant communities towards species from warmer regions, a process termed ‘thermophilization’. In forests, canopy disturbances such as fire may hasten this process by increasing temperature and moisture stress in the understory, yet little is known about the mechanisms that might drive such shifts, or the consequences of these processes for plant diversity.

We sampled understory vegetation across a gradient of disturbance severity from a large-scale natural experiment created by the factorial combination of forest thinning and wildfire in California. Using information on evolutionary history and functional traits, we tested the hypothesis that disturbance severity should increase community dominance by species with southern-xeric biogeographic affinities. We also analysed how climatic productivity mediates the effect of disturbance severity, and quantified the functional trait response to disturbance, to investigate potential mechanisms behind thermophilization.

The proportion of north-temperate flora decreased, while the proportion of southern-xeric flora increased, with greater disturbance severity and less canopy closure. Disturbance caused a greater reduction of north-temperate flora in productive (wetter) forests, while functional trait analyses suggested that species colonizing after severe

disturbance may be adapted to increased water stress. Forests with intermediate disturbance severity, where abundances of northern and southern species were most equitable, had the highest stand-scale understory diversity.

<u>Synthesis.</u> Canopy disturbance is likely to accelerate plant community shifts towards species from warmer regions, via its effects on understory microclimate at small scales. Understory diversity can be enhanced by intermediate disturbance regimes that promote the coexistence of species with different biogeographic affinities.

Sun, S., G. Sun, P. Caldwell, S. G. McNulty, E. Cohen, J. Xiao, and Y. Zhang. 2015. **Drought impacts on ecosystem functions of the U.S. National Forests and Grasslands: Part I evaluation of a water and carbon balance model.** Forest Ecology and Management 353: 260-268.

Abstract. Understanding and quantitatively evaluating the regional impacts of climate change and variability (e.g., droughts) on forest ecosystem functions (i.e., water yield, evapotranspiration, and productivity) and services (e.g., fresh water supply and carbon sequestration) is of great importance for developing climate change adaptation strategies for National Forests and Grasslands (NFs) in the United States. However, few reliable continental-scale modeling tools are available to account for both water and carbon dynamics. The objective of this study was to test a monthly water and carbon balance model, the Water Supply Stress Index (WaSSI) model, for potential application in addressing the influences of drought on NFs ecosystem services across the conterminous United States (CONUS). The performance of the WaSSI model was comprehensively assessed with measured streamflow (Q) at 72 U.S. Geological Survey (USGS) gauging stations, and satellite-based estimates of watershed evapotranspiration (ET) and gross primary productivity (GPP) for 170 National Forest and Grassland (NFs). Across the 72 USGS watersheds, the WaSSI model generally captured the spatial variability of multi-year mean annual and monthly Q and annual ET as evaluated by Correlation Coefficient (R = 0.71–1.0), Nash–Sutcliffe Efficiency (NS = 0.31–1.00), and normalized Root Mean Squared Error (0.06–0.48). The modeled ET and GPP by WaSSI agreed well with the remote sensing-based estimates for multi-year annual and monthly means for all the NFs. However, there were systemic discrepancies in GPP between our simulations and the satellite-based estimates on a yearly and monthly scale, suggesting uncertainties in GPP estimates in all methods (i.e., remote sensing and modeling). Overall, our

assessments suggested that the WaSSI model had the capability to reconstruct the long-term forest watershed water and carbon balances at a broad scale. This model evaluation study provides a foundation for model applications in understanding the impacts of climate change and variability (e.g., droughts) on NFs ecosystem service functions.

Sun, S., G. Sun, P. Caldwell, S. McNulty, E. Cohen, J. Xiao, and Y. Zhang. 2015. **Drought impacts on ecosystem functions of the U.S. National Forests and Grasslands: Part II assessment results and management implications.** Forest Ecology and Management 353: 269-279.

Abstract. The 781,000 km2 (193 million acre) United States National Forests and Grasslands system (NF) provides important ecosystem services such as clean water supply, timber production, wildlife habitat, and recreation opportunities to the American public. Quantifying the historical impacts of climate change and drought on ecosystem functions at the national scale is essential to develop sound forest management and watershed restoration plans under a changing climate. This study applied the previously validated Water Supply and Stress Index model (WaSSI) to 170 NFs in the conterminous U.S. (CONUS) to examine how historical extreme droughts have affected forest water yield (Q) and gross primary productivity (GPP). For each NF, we focused on the five years with the lowest annual SPI3 (Standardized Precipitation Index on a 3-month time scale) during 1962–2012. The extent of extreme droughts as measured by the number of NFs and total area affected by droughts has increased during the last decade. Across all lands in CONUS, the most extreme drought during the past decade occurred in 2002, resulting in a mean reduction of Q by 32% and GPP by 20%. For the 170 individual NFs, on average, the top-five droughts represented a reduction in precipitation by 145 mm yr^{-1} (or 22%), causing reductions in evapotranspiration by 29 mm yr^{-1} (or 8%), Q by 110 mm yr^{-1} (or 37%) and GPP by 65 gC m^{-2} yr^{-1} (or 9%). The responses of the forest hydrology and productivity to the top-five droughts varied spatially due to different land-surface characteristics (e.g., climatology and vegetation) and drought severity at each NF. This study provides a comprehensive benchmark assessment of likely drought impacts on the hydrology and productivity in NFs using consistent methods and datasets across the conterminous U.S. The study results are useful to the forestry decision makers for developing appropriate strategies to restore and protect ecosystem services in anticipating potential future droughts and climate change.

Turner, D. P., D. R. Conklin, and J. P. Bolte. 2015. **Projected climate change impacts on forest land cover and land use over the Willamette River Basin, Oregon, USA.** Climatic Change 133: 335-348.

Abstract. Upland forests in the Pacific Northwest currently provide a host of ecosystem services. However, the regional climate is expected to warm significantly over the course of the 21st century and this factor must be accounted for in planning efforts to maintain those services. Here we couple a dynamic global vegetation model (MC2) with a landscape simulation model (Envision) to evaluate potential impacts of climate change on the vegetation cover and the disturbance regime in the Willamette River Basin, Oregon. Three CMIP5 climate model scenarios, downscaled to a 4 km spatial resolution, were employed. In our simulations, the dominant potential vegetation cover type remained forest throughout the basin, but forest type transitioned from primarily evergreen needleleaf to a mixture of broadleaf and needleleaf growth forms adapted to a warmer climate. By 2100, there was a difference (i.e., climate/vegetation disequilibrium) between potential and actual forest type for 20–50% of the forested area. In the moderate to high climate change scenarios, the average area burned per year increased three to nine fold from the present day. Forest harvest on private land is projected to be affected late in the century because of fire altering the availability of rotation-age stands. A generally more disturbed and open forest landscape is expected, which may significantly alter the hydrologic cycle.

Rangeland Vegetation

Dilts, T. E., P. J. Weisberg, C. M. Dencker, and J. C. Chambers. 2015. **Functionally relevant climate variables for arid lands: a climatic water deficit approach for modelling desert shrub distributions.** Journal of Biogeography 42: 1986-1997.

Abstract. Aim. We have three goals. (1) To develop a suite of functionally relevant climate variables for modelling vegetation distribution on arid and semi-arid landscapes of the Great Basin, USA. (2) To compare the predictive power of vegetation distribution models based on mechanistically proximate factors (water deficit variables) and factors that are more mechanistically removed from a plant's use of water (precipitation). (3) To quantify the climate gradients that control shrub distributions in a cold desert environment.

Location. The central basin and range ecoregion of the western USA (36–42°N).

Methods. We used a modified Thornthwaite method to derive monthly water balance variables and to depict them using a water balance climograph. Eighteen variables were calculated from the climograph, representing different components of the seasonal water balance. These were used in boosted regression tree models to derive distribution models for 18 desert shrub species. The water balance approach was compared with an approach that used bioclimatic variables derived from the PRISM (Parameter-elevation Relationships on Independent Slopes Model) climate data.

Results. The water balance and bioclimatic approaches yielded models with similar performance in predicting the geographical distribution of most shrub species. Cumulative annual climatic water deficit was consistently the most important water balance variable for predicting shrub type distributions, although predictions were improved by the inclusion of variables that describe the seasonal distribution of water balance such as water supply in the spring, fall actual evapotranspiration, monsoonality and summer decline in actual evapotranspiration.

Main conclusions. The water balance and bioclimatic approaches to species distribution modelling both yielded similar prediction accuracies. However, the water balance approach offers advantages over the bioclimatic approach because it is mechanistically derived to approximate physical processes important for plant growth.

Eskelinen, A., and S. P. Harrison. 2015. **Resource colimitation governs plant community responses to altered precipitation.** Proceedings of the National Academy of Sciences 112: 13009-13014.

Abstract. Ecological theory and evidence suggest that plant community biomass and composition may often be jointly controlled by climatic water availability and soil nutrient supply. To the extent that such colimitation operates, alterations in water availability caused by climatic change may have relatively little effect on plant communities on nutrient-poor soils. We tested this prediction with a 5-y rainfall and nutrient manipulation in a semiarid annual grassland system with highly heterogeneous soil nutrient supplies. On nutrient-poor soils, rainfall addition alone had little impact, but rainfall and nutrient addition synergized to cause large increases in biomass, declines in diversity, and near-complete species turnover. Plant species with resource-conservative functional traits (low specific leaf area, short stature) were replaced by species with resource-acquisitive functional traits (high specific leaf area, tall stature). On nutrient-rich soils, in contrast, rainfall addition alone caused substantial increases in biomass, whereas fertilization had little effect. Our results highlight that multiple resource limitation is a critical aspect when predicting the relative vulnerability of natural communities to climatically induced compositional change and diversity loss.

Gherardi, L. A., and O. E. Sala. 2015. **Enhanced precipitation variability decreases grass- and increases shrub-productivity.** Proceedings of the National Academy of Sciences 112: 12735-12740.

Abstract. Although projections of precipitation change indicate increases in variability, most studies of impacts of climate change on ecosystems focused on effects of changes in amount of precipitation, overlooking precipitation variability effects, especially at the interannual scale. Here, we present results from a 6-y field experiment, where we applied sequences of wet and dry years, increasing interannual precipitation coefficient of variation while maintaining a precipitation amount constant. Increased precipitation variability significantly reduced ecosystem primary production. Dominant plant-functional types showed opposite responses: perennial-grass productivity decreased by 81%, whereas shrub productivity increased by 67%. This pattern was explained by different nonlinear responses to precipitation. Grass productivity presented a saturating response to precipitation where dry years had a larger negative effect than the positive effects of wet years. In contrast, shrubs showed an increasing response to precipitation that resulted in an increase in average productivity with increasing precipitation variability. In addition, the effects of precipitation variation increased through time. We argue that the differential responses of grasses and shrubs to precipitation variability and the amplification of this phenomenon through time result from contrasting root distributions of grasses and shrubs and competitive interactions among plant types, confirmed by structural equation analysis. Under drought conditions, grasses reduce their abundance and their ability to absorb water that then is transferred to deep soil layers that are exclusively explored by shrubs. Our work addresses an understudied dimension of climate change that might lead to widespread shrub encroachment reducing the provisioning of ecosystem services to society.

Gremer, J. R., J. B. Bradford, S. M. Munson, and M. C. Duniway. 2015. **Desert grassland responses to climate and soil moisture suggest divergent vulnerabilities across the southwestern United States.** Global Change Biology 21: 4049-4062.

Abstract. Climate change predictions include warming and drying trends, which are expected to be particularly pronounced in the southwestern United States. In this region, grassland dynamics are tightly linked to available moisture, yet it has proven difficult to resolve what aspects of climate drive vegetation change. In part, this is because it is unclear how heterogeneity in soils affects plant responses to climate. Here, we combine climate and soil properties with a mechanistic soil water model to explain temporal fluctuations in perennial grass cover, quantify where and the degree to which incorporating soil water dynamics enhances our ability to understand temporal patterns, and explore the potential consequences of climate change by assessing future trajectories of important climate and soil water variables. Our analyses focused on long-term (20–56 years) perennial grass dynamics across the Colorado Plateau, Sonoran, and Chihuahuan Desert regions. Our results suggest that climate variability has negative effects on grass cover, and that precipitation subsidies that extend growing seasons are beneficial. Soil water metrics, including the number of dry days and availability of water from deeper (>30 cm) soil layers, explained additional grass cover variability. While individual climate variables were ranked as more important in explaining grass cover, collectively soil water accounted for 40–60% of the total explained variance. Soil water conditions were more useful for understanding the responses of C3 than C4 grass species. Projections of water balance variables under climate change indicate that conditions that currently support perennial grasses will be less common in the future, and these altered conditions will be more pronounced in the Chihuahuan Desert and Colorado Plateau. We conclude that incorporating multiple aspects of climate and accounting for soil variability can improve our ability to understand patterns, identify areas of vulnerability, and predict the future of desert grasslands.

Isbell, F., D. Craven, J. Connolly, M. Loreau, B. Schmid, C. Beierkuhnlein, T. M. Bezemer, C. Bonin, H. Bruelheide, E. de Luca, A. Ebeling, J. N. Griffin, Q. Guo, Y. Hautier, A. Hector, A. Jentsch, J. Kreyling, V. Lanta, P. Manning, S. T. Meyer, A. S. Mori, S. Naeem, P. A. Niklaus, H. W. Polley, P. B. Reich, C. Roscher, E. W. Seabloom, M. D. Smith, M. P. Thakur, D. Tilman, B. F. Tracy, W. H. van der Putten, J. van Ruijven, A. Weigelt, W. W. Weisser, B. Wilsey, and N. Eisenhauer. 2015. **Biodiversity increases the resistance of ecosystem productivity to climate extremes.** Nature 526: 574-577.

Abstract. It remains unclear whether biodiversity buffers ecosystems against climate extremes, which are becoming increasingly frequent worldwide. Early results suggested that the ecosystem productivity of diverse grassland plant communities was more resistant, changing less during drought, and more resilient, recovering more quickly after drought, than that of depauperate communities. However, subsequent experimental tests produced mixed results. Here we use data from 46 experiments that manipulated grassland plant diversity to test whether biodiversity provides resistance during and resilience after climate events. We show that biodiversity increased ecosystem resistance for a broad range of climate events, including wet or dry, moderate or extreme, and brief or prolonged events. Across all studies and climate events, the productivity of low-diversity communities with one or two species changed by approximately 50% during climate events, whereas that of high-diversity communities with 16–32 species was more resistant, changing by only approximately 25%. By a year after each climate event, ecosystem productivity had often fully recovered, or overshot, normal levels of productivity in both high- and low-diversity communities, leading to no detectable dependence of ecosystem resilience on biodiversity. Our results suggest that biodiversity mainly stabilizes ecosystem productivity, and productivity-dependent ecosystem services, by increasing resistance to climate events. Anthropogenic environmental changes that drive biodiversity loss thus seem likely to decrease ecosystem stability, and restoration of biodiversity to increase it, mainly by changing the resistance of ecosystem productivity to climate events.

Redmond, M. D., N. S. Cobb, M. J. Clifford, and N. N. Barger. 2015. **Woodland recovery following drought-induced tree mortality across an environmental stress gradient.** Global Change Biology 21: 3685-3695.

Abstract. Recent droughts and increasing temperatures have resulted in extensive tree mortality across the globe. Understanding the environmental controls on tree regeneration following these drought events will allow for better predictions of how these ecosystems may shift under a warmer, drier climate. Within the widely distributed piñon–juniper woodlands of the southwestern USA, a multiyear drought in 2002–2004 resulted in extensive adult piñon mortality and shifted adult woodland composition to a juniper-dominated, more savannah-type ecosystem. Here, we used pre- (1998–2001) and 10-year post- (2014) drought stand structure data of individually mapped trees at 42 sites to assess the effects of this drought on tree regeneration across a gradient of environmental stress. We found declines in piñon juvenile densities since the multiyear drought due to limited new recruitment and high (>50%) juvenile mortality. This is in contrast to juniper juvenile densities, which increased over this time period. Across the landscape, piñon recruitment was positively associated with live adult piñon densities and soil available water capacity, likely due to their respective effects on seed and water availability. Juvenile piñon survival was strongly facilitated by certain types of nurse trees and shrubs. These nurse plants also moderated the effects of environmental stress on piñon survival: Survival of interspace piñon juveniles was positively associated with soil available water capacity, whereas survival of nursed piñon juveniles was negatively associated with perennial grass cover. Thus, nurse plants had a greater facilitative effect on survival at sites with higher soil available water capacity and perennial grass cover. Notably, mean annual climatic water deficit and elevation were not associated with piñon recruitment or survival across the landscape. Our findings reveal a clear shift in successional trajectories toward a more juniper-dominated woodland and highlight the importance of incorporating biotic interactions and soil properties into species distribution modeling approaches.

Fish and Wildlife

Feyrer, F., J. E. Cloern, L. R. Brown, M. A. Fish, K. A. Hieb, and R. D. Baxter. 2015. **Estuarine fish communities respond to climate variability over both river and ocean basins.** Global Change Biology 21: 3608-3619.

Abstract. Estuaries are dynamic environments at the land–sea interface that are strongly affected by interannual climate variability. Ocean–atmosphere processes propagate into estuaries from the sea, and atmospheric processes over land propagate into estuaries from watersheds. We examined the effects of these two separate climate-driven processes on pelagic and demersal fish community structure along the salinity gradient in the San Francisco Estuary, California, USA. A 33-year data set (1980–2012) on pelagic and demersal fishes spanning the freshwater to marine regions of the estuary suggested the existence of five estuarine salinity fish guilds: limnetic (salinity = 0–1), oligohaline (salinity = 1–12), mesohaline (salinity = 6–19), polyhaline (salinity = 19–28), and euhaline (salinity = 29–32). Climatic effects propagating from the adjacent Pacific Ocean, indexed by the North Pacific Gyre Oscillation (NPGO), affected demersal and pelagic fish community structure in the euhaline and polyhaline guilds. Climatic effects propagating over land, indexed as freshwater outflow from the watershed (OUT), affected demersal and pelagic fish community structure in the oligohaline, mesohaline, polyhaline, and euhaline guilds. The effects of OUT propagated further down the estuary salinity gradient than the effects of NPGO that propagated up the estuary salinity gradient, exemplifying the role of variable freshwater outflow as an important driver of biotic communities in river-dominated estuaries. These results illustrate how unique sources of climate variability interact to drive biotic communities and, therefore, that climate change is likely to be an important driver in shaping the future trajectory of biotic communities in estuaries and other transitional habitats.

Gedir, J. V., J. W. Cain, G. Harris, and T. T. Turnbull. 2015. **Effects of climate change on long-term population growth of pronghorn in an arid environment.** Ecosphere 6: art189.

Abstract. Climate often drives ungulate population dynamics, and as climates change, some areas may become unsuitable for species persistence. Unraveling the relationships between climate and population dynamics, and projecting them across time, advances ecological understanding that informs and steers sustainable conservation for species. Using pronghorn (Antilocapra americana) as an ecological model, we used a Bayesian approach to analyze long-term population, precipitation, and temperature data from 18 populations in the southwestern United States. We determined which long-term (12 and 24 months) or short-term (gestation trimester and lactation period) climatic conditions best predicted annual rate of population growth (λ). We used these predictions to project population trends through 2090. Projections incorporated downscaled climatic data matched to pronghorn range for each population, given a high and a lower atmospheric CO2 concentration scenario. Since the 1990s, 15 of the pronghorn populations declined in abundance. Sixteen populations demonstrated a significant relationship between precipitation and λ, and in 13 of these, temperature was also significant. Precipitation predictors of λ were highly seasonal, with lactation being the most important period, followed by early and late gestation. The influence of temperature on λ was less seasonal than precipitation, and lacked a clear temporal pattern. The climatic projections indicated that all of these pronghorn populations would experience increased temperatures, while the direction and magnitude of precipitation had high population-specific variation. Models predicted that nine populations would be extirpated or approaching extirpation by 2090. Results were consistent across both atmospheric CO2 concentration scenarios, indicating robustness of trends irrespective of climatic severity. In the southwestern United States, the climate underpinning pronghorn populations is shifting, making conditions increasingly inhospitable to pronghorn persistence. This realization informs and steers conservation and management decisions for pronghorn in North America, while exemplifying how similar research can aid ungulates inhabiting arid regions and confronting similar circumstances elsewhere.

Kilduff, D. P., E. Di Lorenzo, L. W. Botsford, and S. L. H. Teo. 2015. **Changing central Pacific El Niños reduce stability of North American salmon survival rates.** Proceedings of the National Academy of Sciences 112: 10962-10966.

Abstract. Pacific salmon are a dominant component of the northeast Pacific ecosystem. Their status is of concern because salmon abundance is highly variable—including protected stocks, a recently closed fishery, and actively managed fisheries that provide substantial ecosystem services. Variable ocean conditions, such as the Pacific Decadal Oscillation (PDO), have influenced these fisheries, while diminished diversity of freshwater habitats have increased variability via the portfolio effect. We address the question of how recent changes in ocean conditions will affect populations of two salmon species. Since the 1980s, El Niño Southern Oscillation (ENSO) events have been more frequently associated with central tropical Pacific warming (CPW) rather than the canonical eastern Pacific warming ENSO (EPW). CPW is linked to the North Pacific Gyre Oscillation (NPGO), whereas EPW is linked to the PDO, different indicators of northeast Pacific Ocean ecosystem productivity. Here we show that both coho and Chinook salmon survival rates along western North America indicate that the NPGO, rather than the PDO, explains salmon survival since the 1980s. The observed increase in NPGO variance in recent decades was accompanied by an increase in coherence of local survival rates of these two species, increasing salmon variability via the portfolio effect. Such increases in coherence among salmon stocks are usually attributed to controllable freshwater influences such as hatcheries and habitat degradation, but the unknown mechanism underlying the ocean climate effect identified here is not directly subject to management actions.

Pintor, A. F. V., L. Schwarzkopf, and A. K. Krockenberger. 2015. **Rapoport's Rule: Do climatic variability gradients shape range extent?** Ecological Monographs 85: 643-659.

Abstract. The trend of increasing latitudinal range sizes of species towards higher latitudes, known as Rapoport's Rule, has been highly controversial in the literature since it was first proposed by Stevens in 1989. We contend that the question of interest is not whether general global patterns occur, nor whether they support or refute Rapoport's Rule, but whether the mechanism thought to underlie such patterns, the Climatic Variability Hypothesis, is supported. The Climatic Variability Hypothesis suggests that taxa originating from environmentally variable habitats, such as those at high latitudes and altitudes, should evolve wider environmental tolerances, and consequently establish wider distributions along climate gradients than taxa originating from relatively stable habitats. We applied a novel approach, incorporating measures of temperature variability across habitats within species' ranges into models of range size distributions, to determine whether the Climatic Variability Hypothesis applied to three clades of medium-sized ectotherms (lizards) distributed over Australia. Our results show that the Climatic Variability Hypothesis is supported, even in taxa that do not exhibit a traditional Rapoport Effect, due to complex, non-unidirectional climatic gradients in our study area. The results highlight the strong impact of climatic variability on species' physiological tolerances and their associated geographic distributions.

Westley, P. A. H., A. H. Dittman, E. J. Ward, and T. P. Quinn. 2015. **Signals of climate, conspecific density, and watershed features in patterns of homing and dispersal by Pacific salmon.** Ecology 96: 2823-2833.

Abstract. It is widely assumed that rates of dispersal in animal populations are plastic in response to intrinsic and extrinsic cues, yet the factors influencing this plasticity are rarely known. This knowledge gap is surprising given the important role of dispersal in facilitating range shifts that may allow populations to persist in a rapidly changing global climate. We used two decades of tagging and recapture data from 19 hatchery populations of *Oncorhynchus tshawytscha* (Chinook salmon) in the Columbia River, USA, to quantify the effects of regional and local climate conditions, density dependence, watershed features such as area and position on the landscape, and direct anthropogenic influence on dispersal rates by adult salmon during the breeding season. We found that the probability of dispersal, termed “straying” in salmon, is plastic in response to multiple factors and that populations showed varied responses that were largely idiosyncratic. A regional climate index (Pacific Decadal Oscillation), water temperatures in the mainstem Columbia River that was commonly experience by populations during migration, water temperatures in local subbasins unique to each population during the breeding season, migration distance, and density dependence had the strongest effects on dispersal. Patterns of dispersal plasticity in response to commonly experienced conditions were consistent with gene by environment interactions, though we are tentative about this interpretation given the domesticated history of these populations. Overall, our results warn against attempts to predict future range shifts of migratory species without considering population-specific dispersal plasticity, and also caution against the use of few populations to infer species-level patterns. Ultimately, our results provide evidence that analyses that examine the response of dispersal to single factors may be misleading.

Invertebrates

Pardikes, N. A., A. M. Shapiro, L. A. Dyer, and M. L. Forister. 2015. **Global weather and local butterflies: variable responses to a large-scale climate pattern along an elevational gradient.** Ecology 96: 2891-2901.

Abstract. Understanding the spatial and temporal scales at which environmental variation affects populations of plants and animals is an important goal for modern population biology, especially in the context of shifting climatic conditions. The El Niño Southern Oscillation (ENSO) generates climatic extremes of interannual variation, and has been shown to have significant effects on the diversity and abundance of a variety of terrestrial taxa. However, studies that have investigated the influence of such large-scale climate phenomena have often been limited in spatial and taxonomic scope. We used 23 years (1988–2010) of a long-term butterfly monitoring data set to explore associations between variation in population abundance of 28 butterfly species and variation in ENSO-derived sea surface temperature anomalies (SSTA) across 10 sites that encompass an elevational range of 2750 m in the Sierra Nevada mountain range of California. Our analysis detected a positive, regional effect of increased SSTA on butterfly abundance (wetter and warmer years predict more butterfly observations), yet the influence of SSTA on butterfly abundances varied along the elevational gradient, and also differed greatly among the 28 species. Migratory species had the strongest relationships with ENSO-derived SSTA, suggesting that large-scale climate indices are particularly valuable for understanding biotic-abiotic relationships of the most mobile species. In general, however, the ecological effects of large-scale climatic factors are context dependent between sites and species. Our results illustrate the power of long-term data sets for revealing pervasive yet subtle climatic effects, but also caution against expectations derived from exemplar species or single locations in the study of biotic-abiotic interactions.

Temperli, C., T. T. Veblen, S. J. Hart, D. Kulakowski, and A. J. Tepley. 2015. **Interactions among spruce beetle disturbance, climate change and forest dynamics captured by a forest landscape model.** Ecosphere 6: art231.

Abstract. The risk of bark beetle outbreaks is widely predicted to increase because of a warming climate that accelerates temperature-driven beetle population growth and drought stress that impairs host tree defenses. However, few if any studies have explicitly evaluated climatically enhanced beetle population dynamics in relation to climate-driven changes in forest composition and structure that may alter forest suitability for beetle infestation. We synthesized current understanding of the interactions among climate, spruce beetles (*Dendroctonus rufipennis*) and forest dynamics to parameterize and further advance the bark beetle module of a dynamic forest landscape model (LandClim) that also integrates fire and wind disturbance and climate-driven forest succession. We applied the model to a subalpine watershed in northwestern Colorado to examine the mechanisms and feedbacks that may lead to shifts in forest composition and spruce beetle disturbance under three climate change scenarios. Simulation results suggest increased drought- and beetle-induced reduction of large Engelmann spruce (*Picea engelmannii*) trees while Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) increased in dominance throughout the study area under all climate change scenarios. This shift in forest composition and structure counterbalances the enhancing effects of accelerated beetle population development and increased drought-induced susceptibility of spruce to beetles. As a result, we projected a long-term decrease in beetle-induced spruce mortality to below historical values under all climate scenarios at low elevations (<2800 m asl). Beetle-induced spruce mortality above 2800 m asl and under moderate climate change was slightly higher and more variable than under historical conditions but decreased to 36% and 6% of historical values under intermediate and extreme climate change, respectively. Because mechanisms driving beetle disturbance dynamics are similar across different bark beetle species, we argue that the depletion of host trees due to drought and beetle disturbance may also be important in other climate-sensitive beetle-host systems. We advocate for the consideration of climate-driven shifts in forest and disturbance dynamics in devising adaptive management strategies.

Soils and Hydrology

Ferrenberg, S., S. C. Reed, and J. Belnap. 2015. **Climate change and physical disturbance cause similar community shifts in biological soil crusts.** Proceedings of the National Academy of Sciences 112: 12116-12121.

Abstract. Biological soil crusts (biocrusts)—communities of mosses, lichens, cyanobacteria, and heterotrophs living at the soil surface—are fundamental components of drylands worldwide, and destruction of biocrusts dramatically alters biogeochemical processes, hydrology, surface energy balance, and vegetation cover. Although there has been long-standing concern over impacts of physical disturbances on biocrusts (e.g., trampling by livestock, damage from vehicles), there is increasing concern over the potential for climate change to alter biocrust community structure. Using long-term data from the Colorado Plateau, we examined the effects of 10 y of experimental warming and altered precipitation (in full-factorial design) on biocrust communities and compared the effects of altered climate with those of long-term physical disturbance (>10 y of replicated human trampling). Surprisingly, altered climate and physical disturbance treatments had similar effects on biocrust community structure. Warming, altered precipitation frequency [an increase of small (1.2 mm) summer rainfall events], and physical disturbance from trampling all promoted early successional community states marked by dramatic declines in moss cover and increases in cyanobacteria cover, with more variable effects on lichens. Although the pace of community change varied significantly among treatments, our results suggest that multiple aspects of climate change will affect biocrusts to the same degree as physical disturbance. This is particularly disconcerting in the context of warming, as temperatures for drylands are projected to increase beyond those imposed as treatments in our study.

Harpold, A. A., and N. P. Molotch. 2015. **Sensitivity of soil water availability to changing snowmelt timing in the western U.S.** Geophysical Research Letters 42: 2015GL065855.

Abstract. The ecohydrological effects of changing snowmelt are strongly mediated by soil moisture. We utilize 259 Snow Telemetry stations across the western U.S. to address two questions: (1) how do relationships between peak soil moisture (PSM) timing and the day of snow disappearance (DSD) vary across ecoregions and (2) what is the regional sensitivity of PSM timing to earlier DSD associated with warming and drying scenarios? All western U.S. ecoregions showed significant relationships between the timing of PSM and DSD. Changes in the timing of PSM based on warming predicted for the middle and end of the 21st century ranged from 1 to 9 days and from 6 to 17 days among ecoregions, respectively. The maritime ecoregions PSM timing were 2–3 times more sensitive to warming and drying versus the interior mountain ecoregions. This work suggests that soil hydrology modifies the effects of earlier snowmelt on regional streamflow response and vegetation water stress.

McCabe, G., and D. Wolock. 2015. **Increasing Northern Hemisphere water deficit.** Climatic Change 132: 237-249.

Abstract. A monthly water-balance model is used with CRUTS3.1 gridded monthly precipitation and potential evapotranspiration (PET) data to examine changes in global water deficit (PET minus actual evapotranspiration) for the Northern Hemisphere (NH) for the years 1905 through 2009. Results show that NH deficit increased dramatically near the year 2000 during both the cool (October through March) and warm (April through September) seasons. The increase in water deficit near 2000 coincides with a substantial increase in NH temperature and PET. The most pronounced increases in deficit occurred for the latitudinal band from 0 to 40°N. These results indicate that global warming has increased the water deficit in the NH and that the increase since 2000 is unprecedented for the 1905 through 2009 period. Additionally, coincident with the increase in deficit near 2000, mean NH runoff also increased due to increases in P. We explain the apparent contradiction of concurrent increases in deficit and increases in runoff.

O'Neal, M. A., B. Hanson, S. Carisio, and A. Satinsky. 2015. **Detecting recent changes in the areal extent of North Cascades glaciers, USA.** Quaternary Research 84: 151-158.

Abstract. We present an exhaustive spatial analysis using the geographic, geometric, and hypsometric characteristics of 742 North Cascades glaciers to evaluate changes in their areal extents over a half-century period. Our results indicate that, contrary to our initial expectations, glacier change throughout the study region cannot be explained readily by correlations in glacier location, size, or shape. Because of the large error attributable to annual variations in glacier area due to snowpack, no statistically reliable change could be detected for 444 glaciers in our study (a slight majority). Of the North Cascades glaciers that do exhibit detectable change, a majority decreased in area, but nevertheless, some were detectably growing. These findings suggest that the integration of weather patterns over time does not neatly translate into correlations with natural variations in the geometry of glaciers. Our statistical analyses of the changes observed indicate that geometric data from a large number of glaciers, as well as a surprisingly large amount of spatial change, are required for a credible statistical detection of glacier-length and area changes over a short (multidecadal) period of time.

Thakur, M. P., A. Milcu, P. Manning, P. A. Niklaus, C. Roscher, S. Power, P. B. Reich, S. Scheu, D. Tilman, F. Ai, H. Guo, R. Ji, S. Pierce, N. G. Ramirez, A. N. Richter, K. Steinauer, T. Strecker, A. Vogel, and N. Eisenhauer. 2015. **Plant diversity drives soil microbial biomass carbon in grasslands irrespective of global environmental change factors.** Global Change Biology 21: 4076-4085.

Abstract. Soil microbial biomass is a key determinant of carbon dynamics in the soil. Several studies have shown that soil microbial biomass significantly increases with plant species diversity, but it remains unclear whether plant species diversity can also stabilize soil microbial biomass in a changing environment. This question is particularly relevant as many global environmental change (GEC) factors, such as drought and nutrient enrichment, have been shown to reduce soil microbial biomass. Experiments with orthogonal manipulations of plant diversity and GEC factors can provide insights whether plant diversity can attenuate such detrimental effects on soil microbial biomass. Here, we present the analysis of 12 different studies with 14 unique orthogonal plant diversity × GEC manipulations in grasslands, where plant diversity and at least one GEC factor (elevated CO_2, nutrient enrichment, drought, earthworm presence, or warming) were manipulated. Our results show that higher plant diversity significantly enhances soil microbial biomass with the strongest effects in long-term field experiments. In contrast, GEC factors had inconsistent effects with only drought having a significant negative effect. Importantly, we report consistent non-significant effects for all 14 interactions between plant diversity and GEC factors, which indicates a limited potential of plant diversity to attenuate the effects of GEC factors on soil microbial biomass. We highlight that plant diversity is a major determinant of soil microbial biomass in experimental grasslands that can influence soil carbon dynamics irrespective of GEC.

Fire

Barbero, R., J. T. Abatzoglou, N. K. Larkin, C. A. Kolden, and B. Stocks. 2015. **Climate change presents increased potential for very large fires in the contiguous United States.** International Journal of Wildland Fire 24: 892-899.

Abstract. Very large fires (VLFs) have important implications for communities, ecosystems, air quality and fire suppression

expenditures. VLFs over the contiguous US have been strongly linked with meteorological and climatological variability. Building on prior modelling of VLFs (>5000 ha), an ensemble of 17 global climate models were statistically downscaled over the US for climate experiments covering the historic and mid-21st-century periods to estimate potential changes in VLF occurrence arising from anthropogenic climate change. Increased VLF potential was projected across most historically fire-prone regions, with the largest absolute increase in the intermountain West and Northern California. Complementary to modelled increases in VLF potential were changes in the seasonality of atmospheric conditions conducive to VLFs, including an earlier onset across the southern US and more symmetric seasonal extension in the northern regions. These projections provide insights into regional and seasonal distribution of VLF potential under a changing climate, and serve as a basis for future strategic and tactical fire management options.

Calder, W. J., D. Parker, C. J. Stopka, G. Jiménez-Moreno, and B. N. Shuman. 2015. **Medieval warming initiated exceptionally large wildfire outbreaks in the Rocky Mountains.** Proceedings of the National Academy of Sciences 112: 13261-13266.

Abstract. Many of the largest wildfires in US history burned in recent decades, and climate change explains much of the increase in area burned. The frequency of extreme wildfire weather will increase with continued warming, but many uncertainties still exist about future fire regimes, including how the risk of large fires will persist as vegetation changes. Past fire-climate relationships provide an opportunity to constrain the related uncertainties, and reveal widespread burning across large regions of western North America during past warm intervals. Whether such episodes also burned large portions of individual landscapes has been difficult to determine, however, because uncertainties with the ages of past fires and limited spatial resolution often prohibit specific estimates of past area burned. Accounting for these challenges in a subalpine landscape in Colorado, we estimated century-scale fire synchroneity across 12 lake-sediment charcoal records spanning the past 2,000 y. The percentage of sites burned only deviated from the historic range of variability during the Medieval Climate Anomaly (MCA) between 1,200 and 850 y B.P., when temperatures were similar to recent decades. Between 1,130 and 1,030 y B.P., 83% (median estimate) of our sites burned when temperatures increased ~0.5 °C relative to the preceding centuries. Lake-based fire rotation during the MCA decreased to an estimated

120 y, representing a 260% higher rate of burning than during the period of dendroecological sampling (360 to −60 y B.P.). Increased burning, however, did not persist throughout the MCA. Burning declined abruptly before temperatures cooled, indicating possible fuel limitations to continued burning.

Freeborn, P. H., M. A. Cochrane, and W. M. Jolly. 2015. **Relationships between fire danger and the daily number and daily growth of active incidents burning in the northern Rocky Mountains, USA.** International Journal of Wildland Fire 24: 900-910.

Abstract. Daily National Fire Danger Rating System (NFDRS) indices are typically associated with the number and final size of newly discovered fires, or averaged over time and associated with the likelihood and total burned area of large fires. Herein we used a decade (2003–12) of NFDRS indices and US Forest Service (USFS) fire reports to examine daily relationships between fire danger and the number and growth rate of wildfires burning within a single predictive service area (PSA) in the Northern Rockies, USA. Results demonstrate that daily associations can be used to: (1) extend the utility of the NFDRS beyond the discovery date of new fires; (2) examine and justify the temporal window within which daily fire danger indices are averaged and related to total burned area; (3) quantify the probability of managing an active incident as a function of fire danger; and (4) quantify the magnitude and variability of daily fire growth as a function of fire danger. The methods herein can be extended to other areas with a daily history of weather and fire records, and can be used to better inform fire management decisions or to compare regional responses of daily fire activity to changes in fire danger.

Vulnerability

Tuberville, T. D., K. M. Andrews, J. H. Sperry, and A. M. Grosse. 2015. **Use of the NatureServe Climate Change Vulnerability Index as an assessment tool for reptiles and amphibians: lessons learned.** Environmental Management 56: 822-834.

Abstract. Climate change threatens biodiversity globally, yet it can be challenging to predict which species may be most vulnerable. Given the scope of the problem, it is imperative to rapidly assess vulnerability and identify actions to decrease risk. Although a variety of tools have been developed to assess climate change vulnerability, few have been evaluated with regard to their suitability for certain taxonomic groups. Due to their ectothermic physiology, low vagility, and strong association with temporary wetlands, reptiles and amphibians may be particularly vulnerable relative to other groups. Here, we evaluate use of the NatureServe Climate Change Vulnerability Index (CCVI) to assess a large suite of herpetofauna from the Sand Hills Ecoregion of the southeastern United States. Although data were frequently lacking for certain variables (e.g., phenological response to climate change, genetic variation), sufficient data were available to evaluate all 117 species. Sensitivity analyses indicated that results were highly dependent on size of assessment area and climate scenario selection. In addition, several ecological traits common in, but relatively unique to, herpetofauna are likely to contribute to their vulnerability and need special consideration during the scoring process. Despite some limitations, the NatureServe CCVI was a useful tool for screening large numbers of reptile and amphibian species. We provide general recommendations as to how the CCVI tool's application to herpetofauna can be improved through more specific guidance to the user regarding how to incorporate unique physiological and behavioral traits into scoring existing sensitivity factors and through modification to the assessment tool itself.

Willis, S. G., W. Foden, D. J. Baker, E. Belle, N. D. Burgess, J. A. Carr, N. Doswald, R. A. Garcia, A. Hartley, C. Hof, T. Newbold, C. Rahbek, R. J. Smith, P. Visconti, B. E. Young, and S. H. M. Butchart. 2015. **Integrating climate change vulnerability assessments from species distribution models and trait-based approaches.** Biological Conservation 190: 167-178.

Abstract. To accommodate climate-driven changes in biological communities, conservation plans are increasingly making use of models to predict species' responses to climate change. To date, species distribution models have been the most commonly used approach for assessing species' vulnerability to climate change. Biological trait-based approaches, which have emerged recently, and which include consideration of species' sensitivity and adaptive capacity, provide alternative and potentially conflicting vulnerability assessments and present conservation practitioners and planners with difficult choices. Here we discuss the differing objectives and strengths of the approaches, and provide guidance to conservation practitioners for their application. We outline an integrative methodological framework for assessing climate change impacts on species that uses both traditional species distribution modelling approaches and

biological trait-based assessments. We show how these models can be used conceptually as inputs to guide conservation monitoring and planning.

Adaptation

Duveneck, M. J., and R. M. Scheller. 2014. **Climate-suitable planting as a strategy for maintaining forest productivity and functional diversity.** Ecological Applications 25: 1653-1668.

Abstract. Within the time frame of the longevity of tree species, climate change will change faster than the ability of natural tree migration. Migration lags may result in reduced productivity and reduced diversity in forests under current management and climate change. We evaluated the efficacy of planting climate-suitable tree species (CSP), those tree species with current or historic distributions immediately south of a focal landscape, to maintain or increase aboveground biomass, productivity, and species and functional diversity. We modeled forest change with the LANDIS-II forest simulation model for 100 years (2000–2100) at a 2-ha cell resolution and five-year time steps within two landscapes in the Great Lakes region (northeastern Minnesota and northern lower Michigan, USA). We compared current climate to low- and high-emission futures. We simulated a low-emission climate future with the Intergovernmental Panel on Climate Change (IPCC) 2007 B1 emission scenario and the Parallel Climate Model Global Circulation Model (GCM). We simulated a high-emission climate future with the IPCC A1FI emission scenario and the Geophysical Fluid Dynamics Laboratory (GFDL) GCM. We compared current forest management practices (business-as-usual) to CSP management. In the CSP scenario, we simulated a target planting of 5.28% and 4.97% of forested area per five-year time step in the Minnesota and Michigan landscapes, respectively. We found that simulated CSP species successfully established in both landscapes under all climate scenarios. The presence of CSP species generally increased simulated aboveground biomass. Species diversity increased due to CSP; however, the effect on functional diversity was variable. Because the planted species were functionally similar to many native species, CSP did not result in a consistent increase nor decrease in functional diversity. These results provide an assessment of the potential efficacy and limitations of CSP management. These results have management implications for sites where diversity and

productivity are expected to decline. Future efforts to restore a specific species or forest type may not be possible, but CSP may sustain a more general ecosystem service (e.g., aboveground biomass).

Grady, K. C., T. E. Kolb, D. H. Ikeda, and T. G. Whitham. 2015. **A bridge too far: cold and pathogen constraints to assisted migration of riparian forests.** Restoration Ecology 23: 811-820.

Abstract. Assisted migration of warm-adapted genotypes to currently cooler climates may reduce maladaptation from future climate change. Few assisted migration trials have considered limitations of the cooler climates and pathogens currently present at transplant sites. This is especially important to consider in riparian ecosystems that are priority targets for restoration in the western United States as they harbor diverse communities. In an effort to validate assisted migration as an effective strategy for mediating the negative impacts of climate change, we used a provenance trial with replicated genotypes from 19 populations of the foundation riparian tree species, Fremont cottonwood (*Populus fremontii*), transplanted to a cold site to test for genetic variation in growth, mortality, and resistance to shoot blight fungi (*Venturia* sp.). Populations from cool sites had up to 4 times faster growth, 3 times higher survival, and 8 times higher resistance to *Venturia* than populations from warm sites, providing evidence of local adaptation to both climate and pathogenic fungi. Budburst phenology and shoot blight were correlated with frost damage, subsequent shrub-form architecture, and mortality. While climate change models predict 6°C increases, plants transferred distances of 6°C at this time would not perform well; an intermediate transfer distance of less than 3°C would avoid maladaptation to the current environment during assisted migration. Thus, multiple and intermediate transfer phases to supplement local genetic variation will likely be necessary for effective assisted migration to accommodate current environments and large changes in climate.

Nicotra, A. B., E. A. Beever, A. L. Robertson, G. E. Hofmann, and J. O'Leary. 2015. **Assessing the components of adaptive capacity to improve conservation and management efforts under global change.** Conservation Biology 29: 1268-1278.

Abstract. Natural-resource managers and other conservation practitioners are under unprecedented pressure to categorize and quantify the vulnerability of natural systems based on assessment of

the exposure, sensitivity, and adaptive capacity of species to climate change. Despite the urgent need for these assessments, neither the theoretical basis of adaptive capacity nor the practical issues underlying its quantification has been articulated in a manner that is directly applicable to natural-resource management. Both are critical for researchers, managers, and other conservation practitioners to develop reliable strategies for assessing adaptive capacity. Drawing from principles of classical and contemporary research and examples from terrestrial, marine, plant, and animal systems, we examined broadly the theory behind the concept of adaptive capacity. We then considered how interdisciplinary, trait- and triage-based approaches encompassing the oft-overlooked interactions among components of adaptive capacity can be used to identify species and populations likely to have higher (or lower) adaptive capacity. We identified the challenges and value of such endeavors and argue for a concerted interdisciplinary research approach that combines ecology, ecological genetics, and eco-physiology to reflect the interacting components of adaptive capacity. We aimed to provide a basis for constructive discussion between natural-resource managers and researchers, discussions urgently needed to identify research directions that will deliver answers to real-world questions facing resource managers, other conservation practitioners, and policy makers. Directing research to both seek general patterns and identify ways to facilitate adaptive capacity of key species and populations within species, will enable conservation ecologists and resource managers to maximize returns on research and management investment and arrive at novel and dynamic management and policy decisions.

Mitigation

Pace, M. L., S. R. Carpenter, and J. J. Cole. 2015. **With and without warning: managing ecosystems in a changing world.** Frontiers in Ecology and the Environment 13: 460-467.

Abstract. Many ecosystems are likely to experience abrupt changes and extreme conditions due to forces such as climate change. These events and their consequences – including the loss of ecosystem services – may be predictable or may occur without warning. Given these considerations, greater efforts are needed in two areas of research: improvements in early warning capability and advances in the management of ecosystems to enhance resilience. Current research has provided enhanced forecasting ability, scenario analysis, and detection of statistical anomalies that indicate abrupt change, but two key concerns remain: the detection of early warning signs near thresholds of change and the use of such warnings for ecosystem management. Furthermore, there may be no advance warning for some types of abrupt change, reinforcing the need to enhance resilience by managing ecosystems to reduce the possibility of crossing thresholds of change. Designing and implementing large-scale management programs is one way to confront these problems.

Schuetz, J. G., G. M. Langham, C. U. Soykan, C. B. Wilsey, T. Auer, and C. C. Sanchez. 2015. **Making spatial prioritizations robust to climate change uncertainties: a case study with North American birds.** Ecological Applications 25: 1819-1831.

Abstract. Spatial prioritizations are essential tools for conserving biodiversity in the face of accelerating climate change. Uncertainty about species' responses to changing climates can complicate prioritization efforts, however, and delay conservation investment. In an effort to facilitate decision-making, we identified three hypotheses about species' potential responses to climate change based on distinct biological assumptions related to niche flexibility and colonization ability. Using 314 species of North American birds as a test case, we tuned separate spatial prioritizations to each hypothesis and assessed the degree to which assumptions about biological responses affected the perceived conservation value of the landscape and prospects for individual taxa. We also developed a bet-hedging prioritization to minimize the chance that incorrect assumptions would lead to valuable landscapes and species being overlooked in multispecies prioritizations. Collectively, these analyses help to quantify the sensitivity of spatial prioritizations to different assumptions about species' responses to climate change and provide a framework for enabling efficient conservation investment despite substantial biological uncertainty.