Climate Change Quarterly: Spring 2017

Prepared by Louisa Evers, Science and Climate Change Coordinator, Bureau of Land Management, Oregon-Washington State Office.

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Climate Projections

Diffenbaugh, N. S., D. Singh, J. S. Mankin, D. E. Horton, D. L. Swain, D. Touma, A. Charland, Y. Liu, M. Haugen, M. Tsiang, and B. Rajaratnam. 2017. **Quantifying the influence of global warming on unprecedented extreme climate events.** Proceedings of the National Academy of Sciences 114:4881-4886. http://dx.doi.org/10.1073/pnas.1618082114

Abstract. Efforts to understand the influence of historical global warming on individual extreme climate events have increased over the past decade. However, despite substantial progress, events that are unprecedented in the local observational record remain a persistent challenge. Leveraging observations and a large climate model ensemble, we quantify uncertainty in the influence of global warming on the severity and probability of the historically hottest month, hottest day, driest year, and wettest 5-d period for different areas of the globe. We find that historical warming has increased the severity and probability of the hottest month and hottest day of the year at >80% of the available observational area. Our framework also suggests that the historical climate forcing has increased the probability of the driest year and wettest 5-d period at 57% and 41% of the observed area, respectively, although we note important caveats. For the most protracted hot and dry events, the strongest and most widespread contributions of anthropogenic climate forcing occur in the tropics, including increases in probability of at least a factor of 4 for the hottest month and at least a factor of 2 for the driest year. We also demonstrate the ability of our framework to systematically evaluate the role of dynamic and thermodynamic factors such as atmospheric circulation patterns and atmospheric water vapor, and find extremely high statistical confidence that anthropogenic forcing increased the probability of record-low Arctic sea ice extent.

Medhaug, I., M. B. Stolpe, E. M. Fischer, and R. Knutti. 2017. **Reconciling controversies about the 'global warming hiatus'.** Nature 545:41-47. http://dx.doi.org/10.1038/nature22315

Abstract. Between about 1998 and 2012, a time that coincided with political negotiations for preventing climate change, the surface of Earth seemed hardly to warm. This phenomenon, often termed the 'global warming hiatus', caused doubt in the public mind about how well anthropogenic climate change and natural variability are understood. Here we show that apparently contradictory conclusions stem from different definitions of 'hiatus' and from different datasets. A combination of changes in forcing, uptake of heat by the oceans, natural variability and incomplete observational coverage reconciles models and data. Combined with stronger recent warming trends in newer datasets, we are now more confident than ever that human influence is dominant in long-term warming.

Drought

Berg, N., and A. Hall. 2017. **Anthropogenic warming impacts on California snowpack during drought.** Geophysical Research Letters 44:2511-2518. http://dx.doi.org/10.1002/2016GL072104

Abstract. Sierra Nevada climate and snowpack is simulated during the period of extreme drought from 2011 to 2015 and compared to an identical simulation except for the removal of the twentieth century anthropogenic warming. Anthropogenic warming reduced average snowpack levels by 25%, with middle-to-low elevations experiencing reductions between 26 and 43%. In terms of event frequency, return

periods associated with anomalies in 4 year 1 April snow water equivalent are estimated to have doubled, and possibly quadrupled, due to past warming. We also estimate effects of future anthropogenic warmth on snowpack during a drought similar to that of 2011–2015. Further snowpack declines of 60–85% are expected, depending on emissions scenario. The return periods associated with future snowpack levels are estimated to range from millennia to much longer. Therefore, past human emissions of greenhouse gases are already negatively impacting statewide water resources during drought, and much more severe impacts are likely to be inevitable.

Crimmins, M. A., D. B. Ferguson, A. M. Meadow, and J. L. Weiss. 2017. **Discerning "flavors" of drought using climate extremes indices.** Journal of Applied Meteorology and Climatology 56:989-1001. http://dx.doi.org/10.1175/jamc-d-16-0270.1

Abstract. Monitoring drought conditions in arid and semiarid regions characterized by high levels of intra- and interannual hydroclimatic variability is a challenging task. Typical drought-monitoring indices that are based on monthly-scale data lack sufficient temporal resolution to detect hydroclimatic extremes and, when used operationally, may not provide adequate indication of drought status. In a case study focused on the Four Corners region of the southwestern United States, the authors used recently standardized World Meteorological Organization climate extremes indices to discern intra-annual hydroclimatic extremes and diagnose potential drought status in conjunction with the simple metric of annual total precipitation. By applying data-reduction methods to a suite of metrics calculated using daily data for 1950–2014, the authors identified five extremes indices that provided additional insight into interannual hydroclimatic variability. Annual time series of these indices revealed anomalous years characterized by shifts in the seasonal distribution of precipitation and in the intensity and frequency of individual events. The driest 4-yr intervals over the study period, characterized by similar annual and interval total precipitation anomalies, represent dramatically different assemblages of index values, which are interpreted as different "flavors" of drought. In turn, it is expected that varying drought impacts on ecosystems, agricultural systems, and water resources would emerge under these different flavors of drought. Results from this study indicate that operational drought monitoring and historical drought assessments in arid and semiarid regions would benefit from the additional insight that daily-based

hydroclimatic extremes indices provide, especially in light of expected climate change–driven changes to the hydrologic cycle.

Herrera-Estrada, J. E., Y. Satoh, and J. Sheffield. 2017. **Spatiotemporal dynamics of global drought.** Geophysical Research Letters 44:2254-2263. http://dx.doi.org/10.1002/2016GL071768

Plain Language Summary. Droughts are some of the most expensive natural disasters that society has to face, so understanding how they evolve and what are the physical mechanisms that control them is critical for improving our ability to predict them. Past research has focused mostly on how droughts evolve in time over a fixed region and how droughts of a given duration evolve in space. However, little work has been done to study how they evolve in time and space, simultaneously, leading to a significant gap in our understanding of these extreme events. In this work we identify individual drought events between 1979 and 2009 around the world and track them in space and time to analyze their characteristics and behaviors across different continents. We find that some droughts can travel hundreds of kilometers from where they originated (e.g., from the U.S. Southwest to the U.S. Midwest), and that after droughts have grown and become intense enough, they will tend to become even larger and more intense before conditions improve (i.e., conditions will tend to become worse before they become better).

Luo, L., D. Apps, S. Arcand, H. Xu, M. Pan, and M. Hoerling. 2017. **Contribution of temperature and precipitation anomalies to the California drought during 2012–2015.** Geophysical Research Letters 44:3184-3192. http://dx.doi.org/10.1002/2016GL072027

Abstract. The recent multiyear drought over California was characterized by large precipitation deficits and abnormally high temperatures during both wet and dry seasons. This study investigates and quantifies the contributions of precipitation and temperature anomalies to the development of the multiyear drought with a set of modeling experiments where the anomalies are either removed or randomly replaced with other historical observations. The study reveals that precipitation deficits have been largely responsible for producing the extreme agricultural drought (i.e., large soil moisture deficits) while warmer temperatures have only marginally intensified the drought. However, the warmer temperatures over the high-

elevation areas during the wet season have contributed equally or more than the precipitation deficits to the reduction of snowpack. The interplay between temperature and precipitation anomalies in space and time also appears to be important for the drought development.

Carbon and Carbon Storage

Conant, R. T., C. E. P. Cerri, B. B. Osborne, and K. Paustian. 2017. **Grassland management impacts on soil carbon stocks: a new synthesis.** Ecological Applications 27:662-668. http://dx.doi.org/10.1002/eap.1473

Abstract. Grassland ecosystems cover a large portion of Earths' surface and contain substantial amounts of soil organic carbon. Previous work has established that these soil carbon stocks are sensitive to management and land use changes: grazing, species composition, and mineral nutrient availability can lead to losses or gains of soil carbon. Because of the large annual carbon fluxes into and out of grassland systems, there has been growing interest in how changes in management might shift the net balance of these flows, stemming losses from degrading grasslands or managing systems to increase soil carbon stocks (i.e., carbon sequestration). A synthesis published in 2001 assembled data from hundreds of studies to document soil carbon responses to changes in management. Here we present a new synthesis that has integrated data from the hundreds of studies published after our previous work. These new data largely confirm our earlier conclusions: improved grazing management, fertilization, sowing legumes and improved grass species, irrigation, and conversion from cultivation all tend to lead to increased soil C, at rates ranging from 0.105 to more than 1 Mg $C \cdot ha^{-1} \cdot yr^{-1}$. The new data include assessment of three new management practices: fire, silvopastoralism, and reclamation, although these studies are limited in number. The main area in which the new data are contrary to our previous synthesis is in conversion from native vegetation to grassland, where we find that across the studies the average rate of soil carbon stock change is low and not significant. The data in this synthesis confirm that improving grassland management practices and conversion from cropland to grassland improve soil carbon stocks.

Liang, S., M. D. Hurteau, and A. L. Westerling. 2017. **Potential decline in carbon carrying capacity under projected climate-wildfire interactions in the Sierra Nevada.** Scientific Reports 7:2420. http://dx.doi.org/10.1038/s41598-017-02686-0

Abstract. Ecosystem carbon carrying capacity (CCC) is determined by prevailing climate and natural disturbance regimes, conditions that are projected to change significantly. The interaction of changing climate and its effects on disturbance regimes is expected to affect forest regeneration and growth, which may diminish forest carbon (C) stocks and uptake. We modeled landscape C dynamics over 590 years along the latitudinal gradient of the U.S. Sierra Nevada Mountains under climate and area burned by large wildfires projected by late 21st century. We assumed climate and wildfire stabilize at late-21st century conditions (2090–2100) to facilitate analysis of lags between warming and changing CCC. We show that compared with historical (1980–2010) climate and wildfire conditions, projected scenarios would drive a significant decrease of up to 73% in mean total ecosystem carbon (TEC) by the end of the 590-year simulation. Tree regeneration failure due to intensified growing season dryness and increased area burned would substantially decrease forested area, transitioning the system from C sink to source. Our results demonstrate the potential for a lower CCC in the system due to extensive vegetation type conversion from forest to non-forest types, and suggest a decline in the contribution of Sierra Nevada forests to U.S. C sink.

Martin, P. A., A. C. Newton, and J. M. Bullock. 2017. **Impacts of invasive plants on carbon pools depend on both species' traits and local climate.** Ecology 98:1026-1035. http://dx.doi.org/10.1002/ecy.1711

Abstract. Invasive plants can alter ecosystem properties, leading to changes in the ecosystem services on which humans depend. However, generalizing about these effects is difficult because invasive plants represent a wide range of life forms, and invaded ecosystems differ in their plant communities and abiotic conditions. We hypothesize that differences in traits between the invader and native species can be used to predict impacts and so aid generalization. We further hypothesize that environmental conditions at invaded sites modify the effect of trait differences and so combine with traits to predict invasion impacts. To test these hypotheses, we used systematic review to compile data on changes in aboveground and soil carbon pools following non-native plant invasion from studies across

the World. Maximum potential height (H_{max}) of each species was drawn from trait databases and other sources. We used meta-regression to assess which of invasive species' H_{max}, differences in this height trait between native and invasive plants, and climatic water deficit, a measure of water stress, were good predictors of changes in carbon pools following invasion. We found that aboveground biomass in invaded ecosystems relative to uninvaded ones increased as the value of H_{max} of invasive relative to native species increased, but that this effect was reduced in more water stressed ecosystems. Changes in soil carbon pools were also positively correlated with the relative H_{max} of invasive species, but were not altered by water stress. This study is one of the first to show quantitatively that the impact of invasive species on an ecosystem may depend on differences in invasive and native species' traits, rather than solely the traits of invasive species. Our study is also the first to show that the influence of trait differences can be altered by climate. Further developing our understanding of the impacts of invasive species using this framework could help researchers to identify not only potentially dangerous invasive species, but also the ecosystems where impacts are likely to be greatest.

Schaedel, M. S., A. J. Larson, D. L. R. Affleck, R. T. Belote, J. M. Goodburn, and D. S. Page-Dumroese. 2017. **Early forest thinning changes aboveground carbon distribution among pools, but not total amount.** Forest Ecology and Management 389:187-198. http://dx.doi.org/10.1016/j.foreco.2016.12.018

Abstract. Mounting concerns about global climate change have increased interest in the potential to use common forest management practices, such as forest density management with thinning, in climate change mitigation and adaptation efforts. Long-term effects of forest density management on total aboveground C are not well understood, especially for precommercial thinning (PCT) implemented very early in stand development. To assess the climate change mitigation potential of PCT, as well as tradeoffs with climate change adaptation, we examined total aboveground C stores in a 54-year-old western larch (*Larix occidentalis* Nutt.) precommercial thinning experiment to determine how different PCT treatments affect long-term aboveground C storage and distribution among pools. Four aboveground C pools (live overstory, live understory/mid-story, woody detritus, and forest floor) were measured and separated into C accumulated prior to initiation of the current stand (legacy C) and C accumulated by the current stand (non-legacy C). PCT had no influence on the total non-legacy aboveground C stores 54 years after treatment. Live tree C was nearly identical across densities due to much larger trees in low density treatments. Low density stands had more understory and mid-story C while unthinned plots had significantly more non-legacy woody detritus C than thinned stands. Legacy pools did not vary significantly with density, but made up a substantial proportion of aboveground C stores. We found that: (1) fifty-four years after PCT total aboveground C is similar across treatments, due primarily to the increase in mean tree C of trees grown at lower stand densities; (2) deadwood legacies from the pre-disturbance forest still play an important role in long-term C storage 62 years after current stand initiation, accounting for approximately 20–25% of aboveground C stores; and (3) given enough time since early thinning, there is no trade-off between managing stands to promote individual tree growth and development of understory vegetation, and maximizing stand level accumulation of aboveground C over the long term. We infer that early PCT can be used to simultaneously achieve climate change mitigation and adaptation objectives, provided treatments are implemented early in stand development before canopy closure and the onset of intense intertree competition.

Zhou, G., X. Zhou, Y. He, J. Shao, Z. Hu, R. Liu, H. Zhou, and S. Hosseinibai. 2017. **Grazing intensity significantly affects belowground carbon and nitrogen cycling in grassland ecosystems: a meta-analysis.** Global Change Biology 23:1167-1179. http://dx.doi.org/10.1111/gcb.13431

Abstract. Livestock grazing activities potentially alter ecosystem carbon (C) and nitrogen (N) cycles in grassland ecosystems. Despite the fact that numerous individual studies and a few meta-analyses had been conducted, how grazing, especially its intensity, affects belowground C and N cycling in grasslands remains unclear. In this study, we performed a comprehensive meta-analysis of 115 published studies to examine the responses of 19 variables associated with belowground C and N cycling to livestock grazing in global grasslands. Our results showed that, on average, grazing significantly decreased belowground C and N pools in grassland ecosystems, with the largest decreases in microbial biomass C and N (21.62% and 24.40%, respectively). In contrast, belowground fluxes, including soil respiration, soil net N mineralization and soil N nitrification increased by 4.25%, 34.67% and 25.87%, respectively, in grazed grasslands compared to ungrazed ones. More importantly, grazing intensity significantly affected the magnitude (even direction) of changes in the majority of the assessed belowground C and N pools and fluxes, and C:N ratio as well as soil moisture. Specifically, light grazing contributed

to soil C and N sequestration whereas moderate and heavy grazing significantly increased C and N losses. In addition, soil depth, livestock type and climatic conditions influenced the responses of selected variables to livestock grazing to some degree. Our findings highlight the importance of the effects of grazing intensity on belowground C and N cycling, which may need to be incorporated into regional and global models for predicting effects of human disturbance on global grasslands and assessing the climate-biosphere feedbacks.

Phenology Changes

Wolf, A. A., E. S. Zavaleta, and P. C. Selmants. 2017. **Flowering phenology shifts in response to biodiversity loss.** Proceedings of the National Academy of Sciences 114:3463-3468. http://dx.doi.org/10.1073/pnas.1608357114

Abstract. Observational studies and experimental evidence agree that rising global temperatures have altered plant phenology—the timing of life events, such as flowering, germination, and leaf-out. Other large-scale global environmental changes, such as nitrogen deposition and altered precipitation regimes, have also been linked to changes in flowering times. Despite our increased understanding of how abiotic factors influence plant phenology, we know very little about how biotic interactions can affect flowering times, a significant knowledge gap given ongoing human-caused alteration of biodiversity and plant community structure at the global scale. We experimentally manipulated plant diversity in a California serpentine grassland and found that many plant species flowered earlier in response to reductions in diversity, with peak flowering date advancing an average of 0.6 days per species lost. These changes in phenology were mediated by the effects of plant diversity on soil surface temperature, available soil N, and soil moisture. Peak flowering dates were also more dispersed among species in high-diversity plots than expected based on monocultures. Our findings illustrate that shifts in plant species composition and diversity can alter the timing and distribution of flowering events, and that these changes to phenology are similar in magnitude to effects induced by climate change. Declining diversity could thus contribute to or exacerbate phenological changes attributed to rising global temperatures.

Species Range Changes

Case, M. J., and J. J. Lawler. 2017. **Integrating mechanistic and empirical model projections to assess climate impacts on tree species distributions in northwestern North America.** Global Change Biology 23:2005-2015. http://dx.doi.org/10.1111/gcb.13570

Abstract. Empirical and mechanistic models have both been used to assess the potential impacts of climate change on species distributions, and each modeling approach has its strengths and weaknesses. Here, we demonstrate an approach to projecting climate-driven changes in species distributions that draws on both empirical and mechanistic models. We combined projections from a dynamic global vegetation model (DGVM) that simulates the distributions of biomes based on basic plant functional types with projections from empirical climatic niche models for six tree species in northwestern North America. These integrated model outputs incorporate important biological processes, such as competition, physiological responses of plants to changes in atmospheric CO_2 concentrations, and fire, as well as what are likely to be species-specific climatic constraints. We compared the integrated projections to projections from the empirical climatic niche models alone. Overall, our integrated model outputs projected a greater climate-driven loss of potentially suitable environmental space than did the empirical climatic niche model outputs alone for the majority of modeled species. Our results also show that refining species distributions with DGVM outputs had large effects on the geographic locations of suitable habitat. We demonstrate one approach to integrating the outputs of mechanistic and empirical niche models to produce bioclimatic projections. But perhaps more importantly, our study reveals the potential for empirical climatic niche models to over-predict suitable environmental space under future climatic conditions.

Currie, D. J., and S. Venne. 2017. **Climate change is not a major driver of shifts in the geographical distributions of North American birds.** Global Ecology and Biogeography 26:333-346. http://dx.doi.org/10.1111/geb.12538

Abstract. Aim: Many studies postulate that physiological tolerance of climatic variables imposes the primary limit on species geographical distributions, that tolerances are constant through time, that climate has warmed and that geographical distributions shift to maintain species in their thermal niches when climate changes. However, recent

studies present evidence that is inconsistent with each of these propositions. Here we ask: how strongly did avian species entire geographical distributions (as opposed to their latitudinal extremes) in North America track temperature changes between 1979 and 2010?

Location: The continental United States (excluding Alaska) and southern Canada.

Methods: We examined changes from 1979 to 2010 in the geographical distributions, and the realized temperature niches, of 21 species of passerine birds whose entire breeding ranges fall within the area well sampled by the North American Breeding Bird Survey. We related changes in breeding distributions to the concomitant changes in breeding season temperature.

Results: The median temperature increased within the breeding ranges of most, but not all, species. Temperature on the coolest 2.5% of routes increased significantly for only 8 of 21 species. Most species' distributions shifted geographically, but the most frequent shift was westward, not northward. Most species' realized temperature niches changed detectably through time, mainly as a result of changing temperature (versus geographical shifts). Where shifts in geographical distribution occurred, in most cases they did not result in smaller changes in species realized temperature niche than species would have experienced by not moving at all. There is little suggestion of a lagged response to climate change.

Main conclusions: We find only slight evidence that the geographical distributions of North American passeriform birds, considered in their entirety (as opposed to their latitudinal extremes), tracked temperature change. Of the factors that have driven recent shifts in the geographical distributions of North American avian species temperature change is probably only a minor one.

Fortini, L., and O. Schubert. 2017. **Beyond exposure, sensitivity and adaptive capacity: a response based ecological framework to assess species climate change vulnerability.** Climate Change Responses 4:2. http://dx.doi.org/10.1186/s40665-017-0030-y

Abstract. As the impacts of global climate change on species are increasingly evident, there is a clear need to adapt conservation efforts worldwide. Species vulnerability assessments (VAs) are increasingly used to summarize all relevant information to determine a species' potential vulnerability to climate change and are frequently the first step in informing climate adaptation efforts. VAs commonly integrate multiple sources of information by utilizing a framework that distinguishes factors relevant to species exposure, sensitivity, and adaptive capacity. However, this framework was originally developed for human systems, and its use to evaluate species vulnerability has serious practical and theoretical limitations. By instead defining vulnerability as the degree to which a species is unable to exhibit any of the responses necessary for persistence under climate change (i.e., toleration of projected changes, migration to new climate-compatible areas, enduring in microrefugia, and evolutionary adaptation), we can bring VAs into the realm of ecological science without applying borrowed abstract concepts that have consistently challenged species-centric research and management. This response-based framework to assess species vulnerability to climate change allows better integration of relevant ecological data and past research, yielding results with much clearer implications for conservation and research prioritization.

Ralston, J., W. V. DeLuca, R. E. Feldman, and D. I. King. 2017. **Population trends influence species ability to track climate change.** Global Change Biology 23:1390-1399. http://dx.doi.org/10.1111/gcb.13478

Abstract. Shifts of distributions have been attributed to species tracking their fundamental climate niches through space. However, several studies have now demonstrated that niche tracking is imperfect, that species' climate niches may vary with population trends, and that geographic distributions may lag behind rapid climate change. These reports of imperfect niche tracking imply shifts in species' realized climate niches. We argue that quantifying climate niche shifts and analyzing them for a suite of species reveal general patterns of niche shifts and the factors affecting species' ability to track climate change. We analyzed changes in realized climate niche between 1984 and 2012 for 46 species of North American birds in relation to population trends in an effort to determine whether species differ in the ability to track climate change and whether differences in niche tracking are related to population trends. We found that increasingly abundant species tended to show greater levels of niche expansion (climate space occupied in 2012 but not in 1980) compared to declining species. Declining species had significantly greater niche unfilling (climate space occupied in 1980 but not in 2012) compared to increasing species due to an inability to colonize new sites beyond their range peripheries after climate had changed at sites of occurrence. Increasing species, conversely, were better able to colonize new sites and therefore showed very little niche unfilling. Our results indicate that species with increasing trends are better able to

geographically track climate change compared to declining species, which exhibited lags relative to changes in climate. These findings have important implications for understanding past changes in distribution, as well as modeling dynamic species distributions in the face of climate change.

Forest Vegetation

Creutzburg, M. K., R. M. Scheller, M. S. Lucash, S. D. LeDuc, and M. G. Johnson. 2017. **Forest management scenarios in a changing climate: trade-offs between carbon, timber, and old forest.** Ecological Applications 27:503-518. http://dx.doi.org/10.1002/eap.1460

Abstract. Balancing economic, ecological, and social values has long been a challenge in the forests of the Pacific Northwest, where conflict over timber harvest and old-growth habitat on public lands has been contentious for the past several decades. The Northwest Forest Plan, adopted two decades ago to guide management on federal lands, is currently being revised as the region searches for a balance between sustainable timber yields and habitat for sensitive species. In addition, climate change imposes a high degree of uncertainty on future forest productivity, sustainability of timber harvest, wildfire risk, and species habitat. We evaluated the long-term, landscape-scale trade-offs among carbon (C) storage, timber yield, and old forest habitat given projected climate change and shifts in forest management policy across 2.1 million hectares of forests in the Oregon Coast Range. Projections highlight the divergence between private and public lands under business-as-usual forest management, where private industrial forests are heavily harvested and many public (especially federal) lands increase C and old forest over time but provide little timber. Three alternative management scenarios altering the amount and type of timber harvest show widely varying levels of ecosystem C and old-forest habitat. On federal lands, ecological forestry practices also allowed a simultaneous increase in old forest and natural early-seral habitat. The ecosystem C implications of shifts away from current practices were large, with current practices retaining up to 105 Tg more C than the alternative scenarios by the end of the century. Our results suggest climate change is likely to increase forest productivity by 30–41% and total ecosystem C storage by 11–15% over the next century as warmer winter temperatures allow greater forest productivity in cooler months. These gains in C storage are unlikely to

be offset by wildfire under climate change, due to the legacy of management and effective fire suppression. Our scenarios of future conditions can inform policy makers, land managers, and the public about the potential effects of land management alternatives, climate change, and the trade-offs that are inherent to management and policy in the region.

Halofsky, J. S., J. E. Halofsky, M. A. Hemstrom, A. T. Morzillo, X. Zhou, and D. C. Donato. 2017. **Divergent trends in ecosystem services under different climate-management futures in a fire-prone forest landscape.** Climatic Change 142:83-95. http://dx.doi.org/10.1007/s10584-017-1925-0

Abstract. While ecosystem services and climate change are often examined independently, quantitative assessments integrating these fields are needed to inform future land management decisions. Using climate-informed state-and-transition simulations, we examined projected trends and tradeoffs for a suite of ecosystem services under four climate change scenarios and two management scenarios (active management emphasizing fuel treatments and no management other than fire suppression) in a fire-prone landscape of dry and moist mixed-conifer forests in central Oregon, USA. Focal ecosystem services included fire potential (regulating service), timber volume (provisioning service), and potential wildlife habitat (supporting service). Projections without climate change suggested active management in dry mixed-conifer forests would create more open forest structures, reduce crown fire potential, and maintain timber stocks, while in moist mixed-conifer forests, active management would reduce crown fire potential but at the expense of timber stocks. When climate change was considered, however, trends in most ecosystem services changed substantially, with large increases in wildfire area predominating broad-scale trends in outputs, regardless of management approach (e.g., strong declines in timber stocks and habitat for closed-forest wildlife species). Active management still had an influence under a changing climate, but as a moderator of the strong climate-driven trends rather than being a principal driver of ecosystem service outputs. These results suggest projections of future ecosystem services that do not consider climate change may result in unrealistic expectations of benefits.

Hember, R. A., W. A. Kurz, and N. C. Coops. 2017. **Relationships between individual-tree mortality and water-balance variables indicate positive trends in water stress-induced tree mortality across North America.** Global Change Biology 23:1691-1710. http://dx.doi.org/10.1111/gcb.13428

Abstract. Accounting for water stress-induced tree mortality in forest productivity models remains a challenge due to uncertainty in stress tolerance of tree populations. In this study, logistic regression models were developed to assess species-specific relationships between probability of mortality (P_m) and drought, drawing on 8.1 million observations of change in vital status (m) of individual trees across North America. Drought was defined by standardized (relative) values of soil water content ($W_{s,z}$) and reference evapotranspiration ($ET_{r,z}$) at each field plot. The models additionally tested for interactions between the water-balance variables, aridity class of the site (AC), and estimated tree height (h). Considering drought improved model performance in 95 (80) per cent of the 64 tested species during calibration (cross-validation). On average, sensitivity to relative drought increased with site AC (i.e. aridity). Interaction between water-balance variables and estimated tree height indicated that drought sensitivity commonly decreased during early height development and increased during late height development, which may reflect expansion of the root system and decreasing whole-plant, leaf-specific hydraulic conductance, respectively. Across North America, predictions suggested that changes in the water balance caused mortality to increase from 1.1% yr^{-1} in 1951 to 2.0% yr^{-1} in 2014 (a net change of 0.9 ± 0.3% yr^{-1}). Interannual variation in mortality also increased, driven by increasingly severe droughts in 1988, 1998, 2006, 2007 and 2012. With strong confidence, this study indicates that water stress is a common cause of tree mortality. With weak-to-moderate confidence, this study strengthens previous claims attributing positive trends in mortality to increasing levels of water stress. This 'learn-as-we-go' approach – defined by sampling rare drought events as they continue to intensify – will help to constrain the hydraulic limits of dominant tree species and the viability of boreal and temperate forest biomes under continued climate change.

Keane, R. E., L. M. Holsinger, M. F. Mahalovich, and D. F. Tomback. 2017. **Evaluating future success of whitebark pine ecosystem restoration under climate change using simulation modeling.** Restoration Ecology 25:220-233. http://dx.doi.org/10.1111/rec.12419

Abstract. Major declines of whitebark pine forests throughout western North America from the combined effects of mountain pine beetle (*Dendroctonus ponderosae*) outbreaks, fire exclusion policies, and the exotic disease white pine blister rust (WPBR) have spurred many restoration actions. However, projected future warming and drying may further exacerbate the species' decline and possibly compromise long-term success of today's restoration activities. We evaluated successes of restoration treatments under future climate using a comprehensive landscape simulation experiment. The spatially explicit, ecological process model FireBGCv2 was used to simulate whitebark pine populations on two U.S. Northern Rocky Mountain landscapes over 95 years under two climate, three restoration, and two fire management scenarios. Major findings were that (1) whitebark pine can remain on some high mountain landscapes in a future climate albeit at lower basal areas (50% decrease), (2) restoration efforts, such as thinning and prescribed burning, are vital to ensure future whitebark pine forests, and (3) climate change impacts on whitebark pine vary by local setting. Whitebark pine restoration efforts will mostly be successful in the future but only if future populations are somewhat resistant to WPBR. Results were used to develop general guidelines that address climate change impacts for planning, designing, implementing, and evaluating fine-scale restoration activities.

Liang, S., M. D. Hurteau, and A. L. Westerling. 2017. **Response of Sierra Nevada forests to projected climate–wildfire interactions.** Global Change Biology 23:2016-2030. http://dx.doi.org/10.1111/gcb.13544

Abstract. Climate influences forests directly and indirectly through disturbance. The interaction of climate change and increasing area burned has the potential to alter forest composition and community assembly. However, the overall forest response is likely to be influenced by species-specific responses to environmental change and the scale of change in overstory species cover. In this study, we sought to quantify how projected changes in climate and large wildfire size would alter forest communities and carbon (C) dynamics, irrespective of competition from nontree species and potential changes in other fire regimes, across the Sierra Nevada, USA. We used a species-specific, spatially explicit forest landscape model (LANDIS-II) to evaluate forest response to climate–wildfire interactions under historical (baseline) climate and climate projections from three climate models (GFDL, CCSM3, and CNRM) forced by a medium–high emission scenario (A2) in combination with corresponding climate-specific large wildfire projections. By late century, we found modest changes in the spatial distribution of dominant species by biomass relative to baseline, but extensive changes in recruitment distribution. Although forest recruitment declined across much of the Sierra, we found that projected climate and wildfire favored the recruitment of more drought-tolerant species over less drought-tolerant species relative to baseline, and this change was greatest at mid-elevations. We also found that projected climate and wildfire decreased tree species richness across a large proportion of the study area and transitioned more area to a C source, which reduced landscape-level C sequestration potential. Our study, although a conservative estimate, suggests that by late century, forest community distributions may not change as intact units as predicted by biome-based modeling, but are likely to trend toward simplified community composition as communities gradually disaggregate and the least tolerant species are no longer able to establish. The potential exists for substantial community composition change and forest simplification beyond this century.

O'Connor, C. D., D. A. Falk, A. M. Lynch, T. W. Swetnam, and C. P. Wilcox. 2017. **Disturbance and productivity interactions mediate stability of forest composition and structure.** Ecological Applications 27:900-915. http://dx.doi.org/10.1002/eap.1492

Abstract. Fire is returning to many conifer-dominated forests where species composition and structure have been altered by fire exclusion. Ecological effects of these fires are influenced strongly by the degree of forest change during the fire-free period. Response of fire-adapted species assemblages to extended fire-free intervals is highly variable, even in communities with similar historical fire regimes. This variability in plant community response to fire exclusion is not well understood; however, ecological mechanisms such as individual species' adaptations to disturbance or competition and underlying site characteristics that facilitate or impede establishment and growth have been proposed as potential drivers of assemblage response. We used spatially explicit dendrochronological reconstruction of tree population dynamics and fire regimes to examine the influence of historical

disturbance frequency (a proxy for adaptation to disturbance or competition), and potential site productivity (a proxy for underlying site characteristics) on the stability of forest composition and structure along a continuous ecological gradient of pine, dry mixed-conifer, mesic mixed-conifer, and spruce–fir forests following fire exclusion. While average structural density increased in all forests, species composition was relatively stable in the lowest productivity pine-dominated and highest productivity spruce–fir-dominated sites immediately following fire exclusion and for the next 100 years, suggesting site productivity as a primary control on species composition and structure in forests with very different historical fire regimes. Species composition was least stable on intermediate productivity sites dominated by mixed-conifer forests, shifting from primarily fire-adapted species to competition-adapted, fire-sensitive species within 20 years of fire exclusion. Rapid changes to species composition and stand densities have been interpreted by some as evidence of high-severity fire. We demonstrate that the very different ecological process of fire exclusion can produce similar changes by shifting selective pressures from disturbance-mediated to productivity-mediated controls. Restoring disturbance-adapted species composition and structure to intermediate productivity forests may help to buffer them against projected increasing temperatures, lengthening fire seasons, and more frequent and prolonged moisture stress. Fewer management options are available to promote adaptation in forest assemblages historically constrained by underlying site productivity.

Swetnam, T. L., P. D. Brooks, H. R. Barnard, A. A. Harpold, and E. L. Gallo. 2017. **Topographically driven differences in energy and water constrain climatic control on forest carbon sequestration.** Ecosphere 8:e01797. http://dx.doi.org/10.1002/ecs2.1797

Abstract. Mountains are vital to ecosystems and human society given their influence on global carbon and water cycles. Yet the extent to which topography regulates montane forest carbon uptake and storage remains poorly understood. To address this knowledge gap, we compared forest aboveground carbon loading to topographic metrics describing energy balance and water availability across three headwater catchments of the Boulder Creek Watershed, Colorado, USA. The catchments range from 1800 to 3500 m above mean sea level with 46–102 cm/yr mean annual precipitation and −1.2° to 12.3°C mean annual temperature. In all three catchments, we found mean forest carbon loading consistently increased from ridges (27 ± 19 Mg C ha) to valley bottoms (60 ± 28 Mg C ha). Low topographic

positions held up to 185 ± 76 Mg C ha, more than twice the peak value of upper positions. Toe slopes fostered disproportionately high net carbon uptake relative to other topographic positions. Carbon storage was on average 20–40 Mg C ha greater on north to northeast aspects than on south to southwest aspects, a pattern most pronounced in the highest elevation, coldest and wettest catchment. Both the peak and mean aboveground carbon storage of the three catchments, crossing an 11°C range in temperature and doubling of local precipitation, defied the expectation of an optimal elevation-gradient climatic zone for net primary production. These results have important implications for models of forest sensitivity to climate change, as well as to predicted estimates of continental carbon reservoirs.

Rangeland Vegetation

Dudney, J., L. M. Hallett, L. Larios, E. C. Farrer, E. N. Spotswood, C. Stein, and K. N. Suding. 2017. **Lagging behind: have we overlooked previous-year rainfall effects in annual grasslands?** Journal of Ecology 105:484-495. http://dx.doi.org/10.1111/1365-2745.12671

Abstract. Rainfall is a key determinant of production and composition in arid and semi-arid systems. Long-term studies relating composition and water availability primarily focus on current-year precipitation patterns, though mounting evidence highlights the importance of previous-year rainfall particularly in grasslands dominated by perennial species. The extent to which lagged precipitation effects occur in annual grasslands, however, remains largely unexplored.

We pair a long-term study with two manipulative experiments to identify patterns and mechanisms of lagged precipitation effects in annual grasslands. The long-term study captured variation in functional group (exotic annual forbs and grasses) abundance and precipitation across 8 years at three northern California grassland sites. We then tested whether lagged rainfall effects were created through seed production and litter (residual dry matter, RDM) by manipulating rainfall and litter, respectively.

Rainfall from the previous-year growing season (both seasonal and total rainfall) shifted functional group abundance. High lagged rainfall was associated with increased grass and decreased forb abundance the following year. Current-year seasonal rainfall also influenced

species composition, with winter rain increasing forb and decreasing grass abundance. Lagged precipitation effects were generally stronger for forbs than for grasses. Our experimental studies provided evidence for two mechanisms that contributed to lagged effects in annual grasslands. Higher rainfall increased seed production for grasses, which translated to more germinable seed the following year. Higher rainfall also increased biomass production and RDM, which benefited grasses and reduced forb abundance.

Synthesis. Our results highlight the importance of previous-year precipitation in structuring annual community composition and suggest two important biotic pathways, seed rain and RDM, that regulate lagged community responses to rainfall. Incorporating lagged effects into models of grassland diversity and productivity could improve predictions of climate change impacts in annual grasslands.

McCollum, D. W., J. A. Tanaka, J. A. Morgan, J. E. Mitchell, W. E. Fox, K. A. Maczko, L. Hidinger, C. S. Duke, and U. P. Kreuter. 2017. **Climate change effects on rangelands and rangeland management: affirming the need for monitoring.** Ecosystem Health and Sustainability 3:e01264. http://dx.doi.org/10.1002/ehs2.1264

Abstract. Uncertainty as to the extent and magnitude of changes in conditions that might occur due to climate change poses a problem for land and resource managers as they seek to adapt to changes and mitigate effects of climate variability. We illustrate using scenarios of projected future conditions on rangelands in the Northern Great Plains and Desert Southwest of the United States. These two regions are different in the ways climate change is projected to affect the regions. Projection of a longer and warmer growing season in the Northern Great Plains could lead to increased forage production and land productivity. Highly uncertain effects on summer monsoons that primarily control rangeland productivity in the Desert Southwest, combined with the possibility of more intense and/or frequent drought events, could present land managers with challenges stemming from decreased forage production and land productivity. Climate projections, though uncertain, provide land managers with basic insight into future conditions they might encounter. They need more. A focus on vulnerability and resilience, with explicit recognition of interactions between ecological and socio-economic factors, coupled with systematic monitoring and assessment of observable conditions on the land to supplement information based on climate projections, will more effectively provide critical and specific information managers

need to adaptively manage rangelands under uncertain climate futures.

Biodiversity

Reside, A. E., J. VanDerWal, and C. Moran. 2017. **Trade-offs in carbon storage and biodiversity conservation under climate change reveal risk to endemic species.** Biological Conservation 207:9-16. http://dx.doi.org/10.1016/j.biocon.2017.01.004

Abstract. Carbon offset funds provide substantial opportunities for protection and restoration of native ecosystems, with corresponding gains for biodiversity and reductions in atmospheric carbon. However, biodiversity could be disadvantaged if not properly accounted for, particularly under climate change, where high carbon gains do not coincide spatially with biodiversity priorities. While globally there is congruence for species richness and carbon stocks, adequate conservation needs to incorporate more refined measures of biodiversity – and consideration of the impact of future climate change. We investigated the spatial trade-off for carbon and biodiversity priorities in north-eastern Australia based on current and projected climate, using the Zonation prioritisation software. By iteratively weighting carbon against biodiversity we found that prioritising land based on biodiversity value (for 697 vertebrates) included priority areas for potential carbon sequestration (Maximum Potential Biomass). However, if prioritisation was based on carbon sequestration potential alone, substantial areas important for biodiversity would be lost. Policy frameworks need to be strengthened to remove barriers from landholder participation in carbon storage projects that have biodiversity benefits, and to require that both carbon and biodiversity gains are additional. Properly accounting for biodiversity in land-based carbon sequestration and storage prioritisation in this region is likely to generate substantial benefits for both biodiversity and carbon.

Fish and Wildlife

Greenberg, C. H., S. J. Zarnoch, and J. D. Austin. 2017. **Weather, hydroregime, and breeding effort influence juvenile recruitment of anurans: implications for climate change.** Ecosphere 8:e01789. http://dx.doi.org/10.1002/ecs2.1789

Abstract. Amphibians that primarily breed in ephemeral wetlands are especially vulnerable to climate change because they rely on rainfall or temperature to initiate breeding and create suitable hydroregimes (water duration, timing, frequency, depth) for reproductive success. Hydroregime effects on reproductive success are likely to differ among species because of differences in reproductive strategies: the length and timing of breeding period, rate of larval development, and timing of metamorphosis. We applied an information-theoretic approach to 22 consecutive years of continuous amphibian trapping data at eight ephemeral wetlands to test hypotheses regarding environmental (hydroregime, weather) and biological (adult breeding effort) factors affecting juvenile recruitment (JR) by six focal species representing four reproductive strategies. We hypothesized that (1) JR by species with similar reproductive strategies would be influenced by similar variables; (2) JR would be higher for all species when models encompassed the maximum time span of potential tadpole occurrence and development; and (3) JR rates within individual wetlands and breeding cycles would correlate most closely between species with similar breeding strategies. The best model for all focal species (except Scaphiopus holbrookii) encompassed the maximum time span and indicated that ≥1 hydroregime variable, total precipitation, or both were important drivers of reproductive success; average air temperature was not. Continuous hydroperiod through peak juvenile emigration was an important predictor of JR for species with prolonged breeding periods, slow larval development, and a “fixed” late spring start date for juvenile emigration (regardless of when oviposition occurred, or cohort age; Lithobates capito, Lithobates sphenocephalus), but not for species with rapid larval development and continual emigration as cohorts complete metamorphosis (Anaxyrus terrestris, Anaxyrus quercicus, Gastrophryne carolinensis, S. holbrookii). Total rainfall was positively associated with recruitment for most species; depth characteristics affected species differently. Annual JR was positively correlated among species with similar reproductive strategies. Our results indicate that weather and hydroregime characteristics interact with reproductive strategies that differ among amphibian species and influence reproductive plasticity, opportunity, and success. Effects of altered weather patterns associated with climate change on amphibian reproductive success

may correspond more closely among species having similar reproductive strategies, with critical implications for population trends and assemblages.

Hagmann, R. K., D. L. Johnson, and K. N. Johnson. 2017. **Historical and current forest conditions in the range of the northern spotted owl in south central Oregon, USA.** Forest Ecology and Management 389:374-385. http://dx.doi.org/10.1016/j.foreco.2016.12.029

Abstract. Restoration to increase resilience to current and projected drought and fire in historically open-canopy forests in fire-prone environments may be constrained by concern for species that favor dense forest conditions. To assist the recovery of a threatened species, the Northern Spotted Owl (NSO), in dry forest environments, the US Fish & Wildlife Service (USFWS) recommends embedding NSO conservation and recovery in restoration efforts that enable ecosystem recovery from past management actions and increase resilience to changing climate. In this study, we assessed changes between historical and current (1) forest structure and composition and (2) extent of NSO nesting and roosting (NR) or foraging (F) forest cover on 39,000 ha at the eastern edge of the current designation of the range of the NSO. Historical records depict a predominantly open-canopy landscape dominated by large ponderosa pine. Current conditions include more than a 600% increase in trees 15–53 cm dbh, substantial decline in trees ⩾81 cm dbh, loss of the widespread distribution of trees ⩾53 cm dbh, and loss of the dominance of ponderosa pine on mixed conifer sites. NSO habitat assessment involves a suite of attributes including: landscape context; species composition; canopy cover; basal area; average tree diameter; diameter diversity; and abundance of large trees, snags, canopy layers, coarse woody debris, and mistletoe. We tested for the presence of forest that met USFWS threshold values for two of these variables, canopy cover and basal area. Historically none of the area met the 60% canopy cover threshold for NR or F forest cover and almost none meets it currently. However, several NSO nesting pairs and individual birds have been observed in the study area over the last 20 years, and studies in other frequent-fire forests show that canopy cover as low as 50% may be functional for NSO. To assess the implications of lower threshold values, we tested for NR or F forest cover presence at half the recommended thresholds, considerably below published estimates. Only five percent of the area exceeded 30% canopy cover historically; much of the current forest exceeds it today. Increase in canopy cover comes at the expense of increasing vulnerability to fire and drought

and loss of historical functions and processes. Conflicting objectives of forest restoration and maintenance of spotted owl habitat on this site – isolated habitat in the dry margin of the range of the NSO – raises questions about how to achieve forest restoration in altered landscapes where existing, novel conditions favor at-risk species.

Isaak, D. J., S. J. Wenger, and M. K. Young. 2017. **Big biology meets microclimatology: defining thermal niches of ectotherms at landscape scales for conservation planning.** Ecological Applications 27:977-990. http://dx.doi.org/10.1002/eap.1501

Abstract. Temperature profoundly affects ecology, a fact ever more evident as the ability to measure thermal environments increases and global changes alter these environments. The spatial structure of thermalscapes is especially relevant to the distribution and abundance of ectothermic organisms, but the ability to describe biothermal relationships at extents and grains relevant to conservation planning has been limited by small or sparse data sets. Here, we combine a large occurrence database of >23000 aquatic species surveys with stream microclimate scenarios supported by an equally large temperature database for a 149000-km mountain stream network to describe thermal relationships for 14 fish and amphibian species. Species occurrence probabilities peaked across a wide range of temperatures (7.0–18.8°C) but distinct warm- or cold-edge distribution boundaries were apparent for all species and represented environments where populations may be most sensitive to thermal changes. Warm-edge boundary temperatures for a native species of conservation concern were used with geospatial data sets and a habitat occupancy model to highlight subsets of the network where conservation measures could benefit local populations by maintaining cool temperatures. Linking that strategic approach to local estimates of habitat impairment remains a key challenge but is also an opportunity to build relationships and develop synergies between the research, management, and regulatory communities. As with any data mining or species distribution modeling exercise, care is required in analysis and interpretation of results, but the use of large biological data sets with accurate microclimate scenarios can provide valuable information about the thermal ecology of many ectotherms and a spatially explicit way of guiding conservation investments.

Levy, O., J. D. Borchert, T. W. Rusch, L. B. Buckley, and M. J. Angilletta. 2017. **Diminishing returns limit energetic costs of climate change.** Ecology 98:1217-1228. http://dx.doi.org/10.1002/ecy.1803

Abstract. Changes in the time available for organisms to maintain physiologically preferred temperatures (thermal opportunity) is a primary mechanism by which climate change impacts the fitness and population dynamics of organisms. Yet, it is unclear whether losses or gains in thermal opportunity result in proportional changes in rates of energy procurement and use. We experimentally quantified lizard food consumption and energy assimilation at different durations of thermal opportunity. We incorporated these data in an individual-based model of foraging and digestion in lizards to explore the implications of nonlinear responses to shifts in thermal opportunity across a wide geographic range. Our model predicts that shifts in thermal opportunities resulting from climate change alter energy intake primarily through digestion rather than feeding, because simulated lizards were able to fill their gut faster than they can digest their food. Moreover, since rates of energy assimilation decelerate with increasing thermal opportunity, shifts in daily energetic assimilation would depend on the previous opportunity for thermoregulation. In particular, the same changes in thermal opportunity will have little impact on lizards from warm locations, while having a large impact on lizards from cold locations where thermoregulation is possible for only a few hours each day. Energy expenditure followed spatial patterns in thermal opportunity, with greater annual energy expenditure occurring at warmer locations. Our model predicts that lizards will spend more energy under climate change by maintaining higher body temperatures and remaining active longer. However, the predicted changes in energy assimilation following climate change greatly exceeded the predicted increases in energy expenditure. Simple models, which assume constant rates of energy gain during activity, will potentially mislead efforts to understand and predict the biological impacts of climate change.

Pacifici, M., P. Visconti, S. H. M. Butchart, J. E. M. Watson, F. M. Cassola, and C. Rondinini. 2017. **Species' traits influenced their response to recent climate change.** Nature Climate Change 7:205-208. http://dx.doi.org/10.1038/nclimate3223

Abstract. Although it is widely accepted that future climatic change—if unabated—is likely to have major impacts on biodiversity, few studies have attempted to quantify the number of species whose populations

have already been impacted by climate change. Using a systematic review of published literature, we identified mammals and birds for which there is evidence that they have already been impacted by climate change. We modelled the relationships between observed responses and intrinsic (for example, body mass) and spatial traits (for example, temperature seasonality within the geographic range). Using this model, we estimated that 47% of terrestrial non-volant threatened mammals (out of 873 species) and 23.4% of threatened birds (out of 1,272 species) may have already been negatively impacted by climate change in at least part of their distribution. Our results suggest that populations of large numbers of threatened species are likely to be already affected by climate change, and that conservation managers, planners and policy makers must take this into account in efforts to safeguard the future of biodiversity.

Rodhouse, T. J., M. Hovland, and M. R. Jeffress. 2017. **Variation in subsurface thermal characteristics of microrefuges used by range core and peripheral populations of the American pika (*Ochotona princeps*)**. Ecology and Evolution 7:1514-1526. http://dx.doi.org/10.1002/ece3.2763

Abstract. Microrefuges provide microclimates decoupled from inhospitable regional climate regimes that enable range-peripheral populations to persist and are important to cold-adapted species in an era of accelerated climate change. However, identifying and describing the thermal characteristics of microrefuge habitats is challenging, particularly for mobile organisms in cryptic, patchy habitats. We examined variation in subsurface thermal conditions of microrefuge habitats among different rock substrate types used by the American pika (*Ochotona princeps*), a climate-sensitive, rock-dwelling Lagomorph. We compared subsurface temperatures in talus and lava substrates in pika survey sites in two US national park units; one park study area on the range periphery and the other in the range core. We deployed paired sensors to examine within-site temperature variation. We hypothesized that subsurface temperatures within occupied sites and structurally complex substrates would be cooler in summer and warmer in winter than unoccupied and less complex sites. Although within-site variability was high, with correlations between paired sensors as low as 47%, we found compelling evidence that pikas occupy microrefuge habitats where subsurface conditions provide more thermal stability than in unoccupied microhabitats. The percentage of days in which microhabitat temperatures were between −2.5 and 25.5°C was significantly higher in occupied sites. Interestingly, thermal conditions were substantially more stable ($p < .05$) in the lava

substrate type identified to be preferentially used by pikas (pahoehoe vs. a'a) in a previous study. Our study and others suggest that thermal stability appears to be the defining characteristic of subsurface microrefuges used by American pikas and is a likely explanation for enigmatic population persistence at the range periphery. Our study exemplifies an integrated approach for studying complex microhabitat conditions, paired with site use surveys and contextualized with information about gene flow provided by complementary studies.

Vanbianchi, C. M., M. A. Murphy, and K. E. Hodges. 2017. **Canada lynx use of burned areas: Conservation implications of changing fire regimes.** Ecology and Evolution 7:2382-2394. http://dx.doi.org/10.1002/ece3.2824

Abstract. A fundamental problem in ecology is forecasting how species will react to major disturbances. As the climate warms, large, frequent, and severe fires are restructuring forested landscapes at large spatial scales, with unknown impacts on imperilled predators. We use the United States federally Threatened Canada lynx as a case study to examine how predators navigate recent large burns, with particular focus on habitat features and the spatial configuration (e.g., distance to edge) that enabled lynx use of these transformed landscapes. We coupled GPS location data of lynx in Washington in an area with several recent large fires and a number of GIS layers of habitat data to develop models of lynx habitat selection in recent burns. Random Forest habitat models showed lynx-selected islands of forest skipped by large fires, residual vegetation, and areas where some trees survived to use newly burned areas. Lynx used burned areas as early as 1 year postfire, which is much earlier than the 2–4 decades postfire previously thought for this predator. These findings are encouraging for predator persistence in the face of fires, but increasingly severe fires or management that reduces postfire residual trees or slow regeneration will likely jeopardize lynx and other predators. Fire management should change to ensure heterogeneity is retained within the footprint of large fires to enable viable predator populations as fire regimes worsen with climate change.

Invertebrates

Matter, S. F., and J. Roland. 2017. **Climate and extreme weather independently affect population growth, but neither is a consistently good predictor.** Ecosphere 8:e01816. http://dx.doi.org/10.1002/ecs2.1816

Abstract. Climate change involves changes in mean temperature and precipitation as well as increases in extreme weather events; thus, determining how species will respond to climate change requires understanding how organisms respond to change in both mean and extreme conditions. Previously, we have shown that the growth of 21 interconnected populations of the alpine butterfly, *Parnassius smintheus*, is affected by prevailing climatic conditions during its overwintering period. More recently, we have shown that population growth is affected by extreme weather events during early overwintering. Here, we compare the descriptive and predictive abilities of models based on climate, weather, and their combination. We found that both climate- and weather-based models explain significant, but independent, variation in year-to-year changes in population abundance; the combination of both was not better than either individual model. None of the models showed consistently good predictive ability. The climate model was accurate in predicting relatively small changes in year-to-year abundance, but not large changes. In contrast, the weather model was poor at predicting small changes in abundance, but accurately predicted large changes. Our results indicate that a more mechanistic approach, linking specific conditions to vital rates and population growth, will be needed to predict population responses to changing abiotic conditions.

Soils and Hydrology

Ferrenberg, S., C. L. Tucker, and S. C. Reed. 2017. **Biological soil crusts: diminutive communities of potential global importance.** Frontiers in Ecology and the Environment 15:160-167. http://dx.doi.org/10.1002/fee.1469

Abstract. Biological soil crusts (biocrusts) are widespread, diverse communities of cyanobacteria, fungi, lichens, and mosses living on soil surfaces, primarily in drylands. Biocrusts can locally govern primary production, soil fertility, hydrology, and surface energy balance, with considerable variation in these functions across alternate community states. Further, these communities have been implicated in Earth

system functioning via potential influences on global biogeochemistry and climate. Biocrusts are easily destroyed by disturbances and appear to be exceptionally vulnerable to warming temperatures and altered precipitation inputs, signaling possible losses of dryland functions with global change. Despite these concerns, we lack sufficient spatiotemporal data on biocrust function, cover, and community structure to confidently assess their ecological roles across the extensive dryland biome. Here, we present the case for cross-scale research and restoration efforts coupled with remote-sensing and modeling approaches that improve our collective understanding of biocrust responses to global change and the ecological roles of these diminutive communities at global scales.

Hicks Pries, C. E., C. Castanha, R. C. Porras, and M. S. Torn. 2017. **The whole-soil carbon flux in response to warming.** Science 355:1420-1423. http://dx.doi.org/10.1126/science.aal1319

Abstract. Soil organic carbon harbors three times as much carbon as Earth's atmosphere, and its decomposition is a potentially large climate change feedback and major source of uncertainty in climate projections. The response of whole-soil profiles to warming has not been tested in situ. In a deep warming experiment in mineral soil, we found that CO_2 production from all soil depths increased with 4°C warming; annual soil respiration increased by 34 to 37%. All depths responded to warming with similar temperature sensitivities, driven by decomposition of decadal-aged carbon. Whole-soil warming reveals a larger soil respiration response than many in situ experiments (most of which only warm the surface soil) and models.

Trancoso, R., J. R. Larsen, T. R. McVicar, S. R. Phinn, and C. A. McAlpine. 2017. **CO_2-vegetation feedbacks and other climate changes implicated in reducing base flow.** Geophysical Research Letters 44:2310-2318. http://dx.doi.org/10.1002/2017GL072759

Abstract. Changes in the hydrological cycle have a significant impact in water limited environments. Globally, some of these regions are experiencing declining precipitation yet are simultaneously becoming greener, partly due to vegetation feedbacks associated with increasing atmospheric CO_2 concentrations. Reduced precipitation together with increasing rates of actual evapotranspiration diminishes streamflow, especially base flow, a critical freshwater dry-season resource. Here we assess recent changes in base flow in Australia from 1981–2013 and 1950–2013 and separate the contribution of precipitation, potential evapotranspiration, and other factors on base flow trends. Our findings reveal that these other factors influencing the base flow trends are best explained by an increase in photosynthetic activity. These results provide the first robust observational evidence that increasing atmospheric CO_2 and its associated vegetation feedbacks are reducing base flow in addition to other climatic impacts. These findings have broad implications for water resource management, especially in the world's water limited regions.

Williams, L., C. Colesie, A. Ullmann, M. Westberg, M. Wedin, and B. Büdel. 2017. **Lichen acclimation to changing environments: Photobiont switching vs. climate-specific uniqueness in *Psora decipiens*.** Ecology and Evolution 7:2560-2574. http://dx.doi.org/10.1002/ece3.2809

Abstract. Unraveling the complex relationship between lichen fungal and algal partners has been crucial in understanding lichen dispersal capacity, evolutionary processes, and responses in the face of environmental change. However, lichen symbiosis remains enigmatic, including the ability of a single fungal partner to associate with various algal partners. *Psora decipiens* is a characteristic lichen of biological soil crusts (BSCs), across semi-arid, temperate, and alpine biomes, which are particularly susceptible to habitat loss and climate change. The high levels of morphological variation found across the range of *Psora decipiens* may contribute to its ability to withstand environmental change. To investigate *Psora decipiens* acclimation potential, individuals were transplanted between four climatically distinct sites across a European latitudinal gradient for 2 years. The effect of treatment was investigated through a morphological examination using light and SEM microscopy; 26S rDNA and rbcL gene analysis assessed site-specific relationships and lichen acclimation through photobiont switching. Initial analysis revealed that many samples had lost their algal layers. Although new growth was often determined, the algae were frequently found to have died without evidence of a new photobiont being incorporated into the thallus. Mycobiont analysis investigated diversity and determined that new growth was a part of the transplant, thus, revealing that four distinct fungal clades, closely linked to site, exist. Additionally, P. decipiens was found to associate with the green algal genus *Myrmecia*, with only two genetically distinct clades between the four sites. Our investigation has suggested that *P. decipiens* cannot acclimate to the substantial climatic variability across its environmental range. Additionally, the

different geographical areas are home to genetically distinct and unique populations. The variation found within the genotypic and morpho-physiological traits of *P. decipiens* appears to have a climatic determinant, but this is not always reflected by the algal partner. Although photobiont switching occurs on an evolutionary scale, there is little evidence to suggest an active environmentally induced response. These results suggest that this species, and therefore, other lichen species, and BSC ecosystems themselves may be significantly vulnerable to climate change and habitat loss.

Fire

Abatzoglou, J. T., C. A. Kolden, A. P. Williams, J. A. Lutz, and A. M. S. Smith. 2017. **Climatic influences on interannual variability in regional burn severity across western US forests.** International Journal of Wildland Fire 26:269-275. http://dx.doi.org/10.1071/WF16165

Abstract. Interannual variability in burn severity is assessed across forested ecoregions of the western United States to understand how it is influenced by variations in area burned and climate during 1984–2014. Strong correlations ($|r| > 0.6$) between annual area burned and climate metrics were found across many of the studied regions. The burn severity of individual fires and fire seasons was weakly, but significantly ($P < 0.05$), correlated with burned area across many regions. Interannual variability in fuel dryness evaluated with fuel aridity metrics demonstrated weak-to-moderate ($|r| > 0.4$) relationships with regional burn severity, congruent with but weaker than those between climate and area burned for most ecoregions. These results collectively suggest that irrespective of other factors, long-term increases in fuel aridity will lead to increased burn severity in western United States forests for existing vegetation regimes.

Davis, R., Z. Yang, A. Yost, C. Belongie, and W. Cohen. 2017. **The normal fire environment—Modeling environmental suitability for large forest wildfires using past, present, and future climate normals.** Forest Ecology and Management 390:173-186. http://dx.doi.org/10.1016/j.foreco.2017.01.027

Abstract. We modeled the normal fire environment for occurrence of large forest wildfires (>40 ha) for the Pacific Northwest Region of the United States. Large forest wildfire occurrence data from the recent climate normal period (1971–2000) was used as the response variable and fire season precipitation, maximum temperature, slope, and elevation were used as predictor variables. A projection of our model onto the 2001–2030 climate normal period showed strong agreement between model predictions and the area of forest burned by large wildfires from 2001 to 2015 (independent fire data). We then used downscaled climate projections for two greenhouse gas concentration scenarios and over 30 climate models to project changes in environmental suitability for large forest fires over the 21st century. Results indicated an increasing proportion of forested area with fire environments more suitable for the occurrence of large wildfires over the next century for all ecoregions but less pronounced for the Coast Range and Puget Lowlands. The largest increases occurred on federal lands, while private and state lands showed less. We calculated fire rotation periods for the recent historical and current climate and examined the relative differences between them and our modeled large wildfire suitability classes. By the end of the century, the models predicted shorter fire rotation periods, with cooler/moister forests experiencing larger magnitudes of change than warmer/drier forests. Modeling products, including a set of time series maps, can provide forest resource managers, fire protection agencies, and policy-makers empirical estimates of how much and where climate change might affect the geographic distribution of large wildfires and effect fire rotations.

Gergel, D. R., B. Nijssen, J. T. Abatzoglou, D. P. Lettenmaier, and M. R. Stumbaugh. 2017. **Effects of climate change on snowpack and fire potential in the western USA.** Climatic Change 141:287-299. http://dx.doi.org/10.1007/s10584-017-1899-y

Abstract. We evaluate the implications of ten twenty-first century climate scenarios for snow, soil moisture, and fuel moisture across the conterminous western USA using the Variable Infiltration Capacity (VIC) hydrology model. A decline in mountain snowpack, an advance in the timing of spring melt, and a reduction in snow season are projected for five mountain ranges in the region. For the southernmost range (the White Mountains), spring snow at most elevations will disappear by the end of the twenty-first century. We investigate soil and fuel moisture changes for the five mountain ranges and for six lowland regions. The accelerated depletion of mountain snowpack due to warming leads to reduced summer soil moisture across mountain environments. Similarly, warmer and drier summers lead to decreases of up to 25% in dead fuel moisture across all mountain ranges. Collective declines in spring mountain snowpack, summer soil moisture, and fuel moisture across western mountain ranges will increase fire potential in flammability-limited forested systems where fuels are not limiting. Projected changes in fire potential in predominately fuel-limited systems at lower elevations are more uncertain given the confounding signals between projected changes in soil moisture and fuel moisture.

Reilly, M. J., C. J. Dunn, G. W. Meigs, T. A. Spies, R. E. Kennedy, J. D. Bailey, and K. Briggs. 2017. **Contemporary patterns of fire extent and severity in forests of the Pacific Northwest, USA (1985–2010).** Ecosphere 8:e01695. http://dx.doi.org/10.1002/ecs2.1695

Abstract. Fire is an important disturbance in many forest landscapes, but there is heightened concern regarding recent wildfire activity in western North America. Several regional-scale studies focus on high-severity fire, but a comprehensive examination at all levels of burn severity (i.e., low, moderate, and high) is needed to inform our understanding of the ecological effects of contemporary fires and how they vary among vegetation zones at sub-regional scales. We integrate Landsat time series data with field measurements of tree mortality to map burn severity in forests of the Pacific Northwest, USA, from 1985 to 2010. We then examine temporal trends in fire extent and spatial patterns of burn severity in relation to drought and annual fire extent. Finally, we compare results among vegetation zones and with expectations based on studies of historical landscape dynamics and fire regimes. Small increases in fire extent over time were associated with drought in all vegetation zones, but fire cumulatively affected <3% of wet vegetation zones, and most dry vegetation zones experienced less fire than expectations from fire history studies. Although the proportion of fire at any level of severity did not increase over time, temporal trends toward larger patches of high-severity fire were related to drought and annual fire extent, depending on vegetation zone. In vegetation zones with historically high-severity regimes, high-severity fire accounted for a large proportion of recent fire extent (43–48%) and occurred primarily in patches ≥100 ha. In vegetation zones with historically low- and mixed-severity regimes, low (45–54%)- and moderate-severity (24–36%) fires were prevalent, but proportions of high-severity fire (23–26%), almost half of which occurred in patches ≥100 ha, were much greater than expectations from most fire history studies. Our results support concerns about large patches of high-severity fire in some dry forests but also suggest that spatial patterns of burn severity across much of the extent burned are generally consistent with current understanding of historical landscape dynamics

in the region. This study highlights the importance of considering the ecological effects of fire at all levels of severity in management and policy initiatives intended to promote forest biodiversity and resilience to future fire activity.

Cultural Resources

Fatorić, S., and E. Seekamp. 2017. **Are cultural heritage and resources threatened by climate change? A systematic literature review.** Climatic Change 142:227-254. http://dx.doi.org/10.1007/s10584-017-1929-9

Abstract. Climate change poses serious threats to the protection and preservation of cultural heritage and resources. Despite a high level of scholarly interest in climate change impacts on natural and socio-economic systems, a comprehensive understanding of the impacts of climate change on cultural heritage and resources across various continents and disciplines is noticeably absent from the literature. To address this gap, we conducted a systematic literature review methodology to identify and characterize the state of knowledge and how the cultural heritage and resources at risk from climate change are being explored globally. Results from 124 reviewed publications show that scholarly interest in the topic is increasing, employs a wide range of research methods, and represents diverse natural and social science disciplines. Despite such increasing and diverse interest in climate change and cultural heritage and resources, the geographic scope of research is limited (predominantly European focused). Additionally, we identified the need for future studies that not only focuses on efficient, sustainable adaptation planning options but also documents if, and how, the implementation of cultural heritage and resources adaptation or preservation is taking place. This systematic literature review can help direct scholarly research in climate change and cultural heritage and resource area. Ultimately, we hope these new directions can influence policy-making for preservation and adaptation of cultural heritage and cultural resources globally.

Adaptation

Doherty, K. D., B. J. Butterfield, and T. E. Wood. 2017. **Matching seed to site by climate similarity: Techniques to prioritize plant materials development and use in restoration.** Ecological Applications 27:1010-1023. http://dx.doi.org/10.1002/eap.1505

Abstract. Land management agencies are increasing the use of native plant materials for vegetation treatments to restore ecosystem function and maintain natural ecological integrity. This shift toward the use of natives has highlighted a need to increase the diversity of materials available. A key problem is agreeing on how many, and which, new accessions should be developed. Here we describe new methods that address this problem. Our methods use climate data to calculate a climate similarity index between two points in a defined extent. This index can be used to predict relative performance of available accessions at a target site. In addition, the index can be used in combination with standard cluster analysis algorithms to quantify and maximize climate coverage (mean climate similarity), given a modeled range extent and a specified number of accessions. We demonstrate the utility of this latter feature by applying it to the extents of 11 western North American species with proven or potential use in restoration. First, a species-specific seed transfer map can be readily generated for a species by predicting performance for accessions currently available; this map can be readily updated to accommodate new accessions. Next, the increase in climate coverage achieved by adding successive accessions can be explored, yielding information that managers can use to balance ecological and economic considerations in determining how many accessions to develop. This approach identifies sampling sites, referred to as climate centers, which contribute unique, complementary, climate coverage to accessions on hand, thus providing explicit sampling guidance for both germplasm preservation and research. We examine how these and other features of our approach add to existing methods used to guide plant materials development and use. Finally, we discuss how these new methods provide a framework that could be used to coordinate native plant materials development, evaluation, and use across agencies, regions, and research groups.

MacLachlan, I. R., T. Wang, A. Hamann, P. Smets, and S. N. Aitken. 2017. **Selective breeding of lodgepole pine increases growth and maintains climatic adaptation.** Forest Ecology and Management 391:404-416. http://dx.doi.org/10.1016/j.foreco.2017.02.008

Abstract. Climate change is disrupting historical patterns of adaptation in temperate and boreal tree species, causing local populations to become maladapted. Tree improvement programs typically utilise local base populations and manage adaptation using geographically defined breeding zones. As climates shift, breeding zones are no longer optimal seed deployment zones because base populations are becoming dissociated from their historical climatic optima. In response, climate-based seed transfer (CBST) policies incorporating assisted gene flow (AGF) are being adopted to pre-emptively match reforestation seedlots with future climates, but their implementation requires accurate knowledge of genetic variation in climatically adaptive traits. Here we use lodgepole pine as a case study to evaluate the effects of selective conifer breeding on adaptive traits and their climatic associations to inform CBST and AGF prescriptions.

Our approach compared 105 natural stand and 20 selectively bred lodgepole pine seedlots from Alberta and British Columbia grown in a common garden of ~2200 seedlings. The effects of selection on phenotypic variation and climatic associations among breeding zones were assessed for growth, phenology and cold hardiness. We found substantial differences between natural and selected seedlings in growth traits, but timing of growth initiation was unaffected, growth cessation was delayed slightly (average 4 days, range 0.7 days to 10 days), and cold injury was slightly greater (average 2.5%, range −7% to 11%) in selected seedlings. Phenotypic differentiation among breeding zones and climatic clines were stronger for all traits in selected seedlings. Height gains resulted from both increased growth rate and delayed growth cessation, but negative indirect effects of selection on cold hardiness were weak.

Selection, breeding and progeny testing combined have produced taller lodgepole pine seedlings that are not adaptively compromised relative to their natural seedling counterparts. Selective breeding produces genotypes that achieve increased height growth and maintain climate adaptation, rather than reconstituting genotypes similar to populations adapted to warmer climates. While CBST is needed to optimise seedlot deployment in new climates, an absence of systematic indirect selection effects on adaptive traits suggests natural and selected seedlots do not require separate AGF prescriptions.

Maher, S. P., T. L. Morelli, M. Hershey, A. L. Flint, L. E. Flint, C. Moritz, and S. R. Beissinger. 2017. **Erosion of refugia in the Sierra Nevada meadows network with climate change.** Ecosphere 8:e01673. http://dx.doi.org/10.1002/ecs2.1673

Abstract. Climate refugia management has been proposed as a climate adaptation strategy in the face of global change. Key to this strategy is identification of these areas as well as an understanding of how they are connected on the landscape. Focusing on meadows of the Sierra Nevada in California, we examined multiple factors affecting connectivity using circuit theory, and determined how patches have been and are expected to be affected by climate change. Connectivity surfaces varied depending upon the underlying hypothesis, although meadow area and elevation were important features for higher connectivity. Climate refugia that would promote population persistence were identified from downscaled climate layers, based on locations with minimal climatic change from historical conditions. This approach was agnostic to specific species, yielding a broad perspective about changes and localized habitats. Connectivity was not a consistent predictor of refugial status in the 20th century, but expected future climate refugia tended to have higher connectivity than those that recently deviated from historical conditions. Climate change is projected to reduce the number of refugial meadows on a variety of climate axes, resulting in a sparser network of potential refugia across elevations. Our approach provides a straightforward method that can be used as a tool to prioritize places for climate adaptation.

Shah, P., M. L. Mallory, A. W. Ando, and G. R. Guntenspergen. 2017. **Fine-resolution conservation planning with limited climate-change information.** Conservation Biology 31:278-289. http://dx.doi.org/10.1111/cobi.12793

Abstract. Climate-change induced uncertainties in future spatial patterns of conservation-related outcomes make it difficult to implement standard conservation-planning paradigms. A recent study translates Markowitz's risk-diversification strategy from finance to conservation settings, enabling conservation agents to use this diversification strategy for allocating conservation and restoration investments across space to minimize the risk associated with such uncertainty. However, this method is information intensive and requires a large number of forecasts of ecological outcomes associated with possible climate-change scenarios for carrying out fine-resolution conservation planning. We developed a technique for iterative, spatial

portfolio analysis that can be used to allocate scarce conservation resources across a desired level of subregions in a planning landscape in the absence of a sufficient number of ecological forecasts. We applied our technique to the Prairie Pothole Region in central North America. A lack of sufficient future climate information prevented attainment of the most efficient risk-return conservation outcomes in the Prairie Pothole Region. The difference in expected conservation returns between conservation planning with limited climate-change information and full climate-change information was as large as 30% for the Prairie Pothole Region even when the most efficient iterative approach was used. However, our iterative approach allowed finer resolution portfolio allocation with limited climate-change forecasts such that the best possible risk-return combinations were obtained. With our most efficient iterative approach, the expected loss in conservation outcomes owing to limited climate-change information could be reduced by 17% relative to other iterative approaches.

Timpane-Padgham, B. L., T. Beechie, and T. Klinger. 2017. **A systematic review of ecological attributes that confer resilience to climate change in environmental restoration.** PLOS ONE 12:e0173812. http://dx.doi.org/10.1371/journal.pone.0173812

Abstract. Ecological restoration is widely practiced as a means of rehabilitating ecosystems and habitats that have been degraded or impaired through human use or other causes. Restoration practices now are confronted by climate change, which has the potential to influence long-term restoration outcomes. Concepts and attributes from the resilience literature can help improve restoration and monitoring efforts under changing climate conditions. We systematically examined the published literature on ecological resilience to identify biological, chemical, and physical attributes that confer resilience to climate change. We identified 45 attributes explicitly related to climate change and classified them as individual- (9), population- (6), community- (7), ecosystem- (7), or process-level attributes (16). Individual studies defined resilience as resistance to change or recovery from disturbance, and only a few studies explicitly included both concepts in their definition of resilience. We found that individual and population attributes generally are suited to species- or habitat-specific restoration actions and applicable at the population scale. Community attributes are better suited to habitat-specific restoration at the site scale, or system-wide restoration at the ecosystem scale. Ecosystem and process attributes vary considerably in their type and applicability. We summarize these relationships in a

decision support table and provide three example applications to illustrate how these classifications can be used to prioritize climate change resilience attributes for specific restoration actions. We suggest that (1) including resilience as an explicit planning objective could increase the success of restoration projects, (2) considering the ecological context and focal scale of a restoration action is essential in choosing appropriate resilience attributes, and (3) certain ecological attributes, such as diversity and connectivity, are more commonly considered to confer resilience because they apply to a wide variety of species and ecosystems. We propose that identifying sources of ecological resilience is a critical step in restoring ecosystems in a changing climate.

Socio-Economics

Lemprière, T. C., E. Krcmar, G. J. Rampley, A. Beatch, C. E. Smyth, M. Hafer, and W. A. Kurz. 2017. **Cost of climate change mitigation in Canada's forest sector.** Canadian Journal of Forest Research 47:604-614. http://dx.doi.org/10.1139/cjfr-2016-0348

Abstract. Managing forests and forest products has substantial potential to help mitigate climate change but the cost has not been extensively examined in Canada. We estimated the cost of seven forest-related mitigation strategies in Canada's 230 million hectares of managed forest, divided into 32 spatial units. For each strategy and spatial unit, we determined forest sector mitigation cost per tonne (t) using estimated impacts on forest sector greenhouse gas emissions and removals and net revenue. National cost curves showed that mitigation averaged 11.0 Mt $CO_2e \cdot year^{-1}$ in 2015–2050 at costs below $50·t CO_2e^{-1} for a strategy of increased recovery of harvested biomass, increased salvage, extraction of harvest residues for bioenergy, and increased production of longer lived products. We also examined national portfolios in which the strategy selected for each spatial unit (from among the seven examined) was chosen to maximize mitigation or minimize costs. At low levels of mitigation, portfolios chosen to minimize costs were much cheaper than those that maximized mitigation, but overall, they yielded less than half the total mitigation of the latter portfolios. Choosing strategies to maximize mitigation in 2015–2050 yielded an average of 16.5 $Mt \cdot year^{-1}$ at costs below $50·t CO_2e^{-1}. Our analysis suggests that forest-

related strategies may be cost-effective choices to help achieve long-term emission reductions in Canada.

Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan, and S. A. Woznicki. 2017. **Climate change and livestock: Impacts, adaptation, and mitigation.** Climate Risk Management 16:145-163. http://dx.doi.org/10.1016/j.crm.2017.02.001

Abstract. Global demand for livestock products is expected to double by 2050, mainly due to improvement in the worldwide standard of living. Meanwhile, climate change is a threat to livestock production because of the impact on quality of feed crop and forage, water availability, animal and milk production, livestock diseases, animal reproduction, and biodiversity. This study reviews the global impacts of climate change on livestock production, the contribution of livestock production to climate change, and specific climate change adaptation and mitigation strategies in the livestock sector. Livestock production will be limited by climate variability as animal water consumption is expected to increase by a factor of three, demand for agricultural lands increase due to need for 70% growth in production, and food security concern since about one-third of the global cereal harvest is used for livestock feed. Meanwhile, the livestock sector contributes 14.5% of global greenhouse gas (GHG) emissions, driving further climate change. Consequently, the livestock sector will be a key player in the mitigation of GHG emissions and improving global food security. Therefore, in the transition to sustainable livestock production, there is a need for: a) assessments related to the use of adaptation and mitigation measures tailored to the location and livestock production system in use, and b) policies that support and facilitate the implementation of climate change adaptation and mitigation measures.