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Climate and Climate Projections

Knutson, T. R., R. Zhang, and L. W. Horowitz. 2016. **Prospects for a prolonged slowdown in global warming in the early 21st century.** Nature Communications 7:13676. http://10.1038/ncomms13676

Abstract. Global mean temperature over 1998 to 2015 increased at a slower rate (0.1 K decade^{-1}) compared with the ensemble mean (forced) warming rate projected by Coupled Model Intercomparison Project 5 (CMIP5) models (0.2 K decade^{-1}). Here we investigate the prospects for this slower rate to persist for a decade or more. The slower rate could persist if the transient climate response is overestimated by CMIP5 models by a factor of two, as suggested by recent low-end estimates. Alternatively, using CMIP5 models' warming rate, the slower rate could still persist due to strong multidecadal internal variability cooling. Combining the CMIP5 ensemble warming rate with internal variability episodes from a single climate model—having the strongest multidecadal variability among CMIP5 models—we estimate that the warming slowdown (<0.1 K decade^{-1} trend beginning in 1998) could persist, due to internal variability cooling, through 2020, 2025 or 2030 with probabilities 16%, 11% and 6%, respectively.

Martinuzzi, S., A. J. Allstadt, B. L. Bateman, P. J. Heglund, A. M. Pidgeon, W. E. Thogmartin, S. J. Vavrus, and V. C. Radeloff. 2016. **Future frequencies of extreme weather events in the National Wildlife Refuges of the conterminous U.S.** Biological Conservation 201:327-335. http://dx.doi.org/10.1016/j.biocon.2016.07.007

Abstract. Climate change is a major challenge for managers of protected areas world-wide, and managers need information about future climate conditions within protected areas. Prior studies of climate change effects in protected areas have largely focused on average climatic conditions. However, extreme weather may have stronger effects on wildlife populations and habitats than changes in averages. Our goal was to quantify future changes in the frequency of extreme heat, drought, and false springs, during the avian breeding season, in 415 National Wildlife Refuges in the conterminous United States. We analyzed spatially detailed data on extreme weather frequencies during the historical period (1950–2005) and under different scenarios of future climate change by mid- and late-21st century. We found that all wildlife refuges will likely experience substantial changes in the frequencies of extreme weather, but the types of projected changes differed among refuges. Extreme heat is projected to increase dramatically in all wildlife refuges, whereas changes in droughts and false springs are projected to increase or decrease on a regional basis. Half of all wildlife refuges are projected to see increases in frequency (> 20% higher than the current rate) in at least two types of weather extremes by mid-century. Wildlife refuges in the Southwest and Pacific Southwest are projected to exhibit the fastest rates of change, and may deserve extra attention. Climate change adaptation strategies in protected areas, such as the U.S. wildlife refuges, may need to seriously consider future changes in extreme weather, including the considerable spatial variation of these changes.

Svejcar, T., R. Angell, and J. James. 2016. **Spatial and temporal variability in minimum temperature trends in the western U.S. sagebrush steppe.** Journal of Arid Environments 133:125-133. http://dx.doi.org/10.1016/j.jaridenv.2016.06.003

Abstract. Climate is a major driver of ecosystem dynamics. In recent years there has been considerable interest in future climate change and potential impacts on ecosystems and management options. In this paper, we analyzed minimum monthly temperature (T min) for ten

rural locations in the western U.S. sagebrush steppe. Oregon and Nevada each had five locations, and the period of record ranged from 69 to 125 years. We used structural time series analysis to evaluate trends over time at each location. We also used box plots to compare variation within months at each location. We concluded: 1) T min variation over years is much higher during the winter than during other seasons, 2) there is evidence of decadal trends in both directions (hotter and cooler) for most, but not all sites, and 3) sites exhibited individualistic patterns rather than following a general regional pattern. The analysis shows that sites in relatively close proximity can exhibit different temperature patterns over time. We suggest that ecologists and land managers make use of any available weather data from local weather stations when planning for the future or interpreting past changes in plant and animal populations, rather than relying on regional averages.

Carbon and Carbon Storage

Corson-Rikert, H. A., S. M. Wondzell, R. Haggerty, and M. V. Santelmann. 2016. **Carbon dynamics in the hyporheic zone of a headwater mountain stream in the Cascade Mountains, Oregon.** Water Resources Research 52:7556-7576. http://10.1002/2016WR019303

Abstract. We investigated carbon dynamics in the hyporheic zone of a steep, forested, headwater catchment western Oregon, USA. Water samples were collected monthly from the stream and a well network during base flow periods. We examined the potential for mixing of different source waters to explain concentrations of DOC and DIC. We did not find convincing evidence that either inputs of deep groundwater or lateral inputs of shallow soil water influenced carbon dynamics. Rather, carbon dynamics appeared to be controlled by local processes in the hyporheic zone and overlying riparian soils. DOC concentrations were low in stream water (0.04–0.09 m*M*), and decreased with nominal travel time through the hyporheic zone (0.02–0.04 m*M* lost over 100 h). Conversely, stream water DIC concentrations were much greater than DOC (0.35–0.7 m*M*) and increased with nominal travel time through the hyporheic zone (0.2–0.4 m*M* gained over 100 h). DOC in stream water could only account for 10% of the observed increase in DIC. In situ metabolic processing of buried particulate organic matter as well as advection of CO_2 from the vadose zone likely accounted for the remaining 90% of the

increase in DIC. Overall, the hyporheic zone was a source of DIC to the stream. We suggest that, in mountain stream networks, hyporheic exchange facilitates the transformation of particulate organic carbon buried in floodplains and transports the DIC that is produced back to the stream where it can be evaded to the atmosphere.

Harris, N. L., S. C. Hagen, S. S. Saatchi, T. R. H. Pearson, C. W. Woodall, G. M. Domke, B. H. Braswell, B. F. Walters, S. Brown, W. Salas, A. Fore, and Y. Yu. 2016. **Attribution of net carbon change by disturbance type across forest lands of the conterminous United States.** Carbon Balance and Management 11:24. http://10.1186/s13021-016-0066-5

Abstract. Background. Locating terrestrial sources and sinks of carbon (C) will be critical to developing strategies that contribute to the climate change mitigation goals of the Paris Agreement. Here we present spatially resolved estimates of net C change across United States (US) forest lands between 2006 and 2010 and attribute them to natural and anthropogenic processes.

Results. Forests in the conterminous US sequestered −460 ± 48 Tg C year^{-1}, while C losses from disturbance averaged 191 ± 10 Tg C year^{-1}. Combining estimates of net C losses and gains results in net carbon change of −269 ± 49 Tg C year^{-1}. New forests gained −8 ± 1 Tg C year^{-1}, while deforestation resulted in losses of 6 ± 1 Tg C year^{-1}. Forest land remaining forest land lost 185 ± 10 Tg C year^{-1} to various disturbances; these losses were compensated by net carbon gains of −452 ± 48 Tg C year^{-1}. C loss in the southern US was highest (105 ± 6 Tg C year^{-1}) with the highest fractional contributions from harvest (92%) and wind (5%). C loss in the western US (44 ± 3 Tg C year^{-1}) was due predominantly to harvest (66%), fire (15%), and insect damage (13%). The northern US had the lowest C loss (41 ± 2 Tg C year^{-1}) with the most significant proportional contributions from harvest (86%), insect damage (9%), and conversion (3%). Taken together, these disturbances reduced the estimated potential C sink of US forests by 42%.

Conclusion. The framework presented here allows for the integration of ground and space observations to more fully inform US forest C policy and monitoring efforts.

Healey, S. P., C. L. Raymond, I. B. Lockman, A. J. Hernandez, C. Garrard, and C. Huang. 2016. **Root disease can rival fire and harvest in reducing forest carbon storage.** Ecosphere 7:e01569. http://10.1002/ecs2.1569

Abstract. Root diseases are known to suppress forest regeneration and reduce growth rates, and they may become more common as susceptible tree species become maladapted in parts of their historic ranges due to climate change. However, current ecosystem models do not track the effects of root disease on net productivity, and there has been little research on how the dynamics of root disease affect carbon (C) storage and productivity across infected landscapes. We compared the effects of root disease against the effects of other types of forest disturbance across six national forest landscapes, 1990–2011. This was enabled by a monitoring tool called the Forest Carbon Management Framework (ForCaMF), which makes use of ground inventory data, an empirical growth model, and time series of Landsat satellite imagery. Despite several large fires that burned across these landscapes during the study period, retrospective ForCaMF analysis showed that fire and root disease had approximately equal impacts on C storage. Relative to C accumulation that would have occurred in their absence, fires from 1990 to 2011 were estimated to reduce regionwide C storage by 215.3 ± 19.1 g/m^2 C, while disease in the same period was estimated to reduce storage by 211.4 ± 59.9 g/m^2 C. Harvest (75.5 ± 13.5 g/m^2 C) and bark beetle activity (14.8 ± 12.5 g/m^2 C) were less important. While long-term disturbance processes such as root disease have generally been ignored by tools informing management of forest C storage, the recent history of several national forests suggests that such disturbances can be just as important to the C cycle as more conspicuous events like wildfires.

Keenan, T. F., I. C. Prentice, J. G. Canadell, C. A. Williams, H. Wang, M. Raupach, and G. J. Collatz. 2016. **Recent pause in the growth rate of atmospheric CO2 due to enhanced terrestrial carbon uptake.** Nature Communications 7:13428. http://10.1038/ncomms13428

Abstract. Terrestrial ecosystems play a significant role in the global carbon cycle and offset a large fraction of anthropogenic CO_2 emissions. The terrestrial carbon sink is increasing, yet the mechanisms responsible for its enhancement, and implications for the growth rate of atmospheric CO_2, remain unclear. Here using global carbon budget estimates, ground, atmospheric and satellite observations, and multiple global vegetation models, we report a

recent pause in the growth rate of atmospheric CO_2, and a decline in the fraction of anthropogenic emissions that remain in the atmosphere, despite increasing anthropogenic emissions. We attribute the observed decline to increases in the terrestrial sink during the past decade, associated with the effects of rising atmospheric CO_2 on vegetation and the slowdown in the rate of warming on global respiration. The pause in the atmospheric CO_2 growth rate provides further evidence of the roles of CO_2 fertilization and warming-induced respiration, and highlights the need to protect both existing carbon stocks and regions, where the sink is growing rapidly.

Ma, X., A. Huete, J. Cleverly, D. Eamus, F. Chevallier, J. Joiner, B. Poulter, Y. Zhang, L. Guanter, W. Meyer, Z. Xie, and G. Ponce-Campos. 2016. **Drought rapidly diminishes the large net CO2 uptake in 2011 over semi-arid Australia.** Scientific Reports 6:37747. http://10.1038/srep37747

Abstract. Each year, terrestrial ecosystems absorb more than a quarter of the anthropogenic carbon emissions, termed as land carbon sink. An exceptionally large land carbon sink anomaly was recorded in 2011, of which more than half was attributed to Australia. However, the persistence and spatially attribution of this carbon sink remain largely unknown. Here we conducted an observation-based study to characterize the Australian land carbon sink through the novel coupling of satellite retrievals of atmospheric CO_2 and photosynthesis and in-situ flux tower measures. We show the 2010–11 carbon sink was primarily ascribed to savannas and grasslands. When all biomes were normalized by rainfall, shrublands however, were most efficient in absorbing carbon. We found the 2010–11 net CO_2 uptake was highly transient with rapid dissipation through drought. The size of the 2010–11 carbon sink over Australia (0.97 Pg) was reduced to 0.48 Pg in 2011–12, and was nearly eliminated in 2012–13 (0.08 Pg). We further report evidence of an earlier 2000–01 large net CO_2 uptake, demonstrating a repetitive nature of this land carbon sink. Given a significant increasing trend in extreme wet year precipitation over Australia, we suggest that carbon sink episodes will exert greater future impacts on global carbon cycle.

Magnússon, R. Í., A. Tietema, J. H. C. Cornelissen, M. M. Hefting, and K. Kalbitz. 2016. Tamm Review: **Sequestration of carbon from coarse woody debris in forest soils.** Forest Ecology and Management 377:1-15. http://dx.doi.org/10.1016/j.foreco.2016.06.033

Abstract. Worldwide, forests have absorbed around 30% of global anthropogenic emissions of carbon dioxide (CO_2) annually, thereby acting as important carbon (C) sinks. It is proposed that leaving large fragments of dead wood, coarse woody debris (CWD), in forest ecosystems may contribute to the forest C sink strength. CWD may take years to centuries to degrade completely, and non-respired C from CWD may enter the forest soil directly or in the form of dissolved organic C. Although aboveground decomposition of CWD has been studied frequently, little is known about the relative size, composition and fate of different C fluxes from CWD to soils under various substrate-specific and environmental conditions. Thus, the exact contribution of C from CWD to C sequestration within forest soils is poorly understood and quantified, although understanding CWD degradation and stabilization processes is essential for effective forest C sink management. This review aims at providing insight into these processes on the interface of forest ecology and soil science, and identifies knowledge gaps that are critical to our understanding of the effects of CWD on the forest soil C sink. It may be seen as a “call-to-action” crossing disciplinary boundaries, which proposes the use of compound-specific analytical studies and manipulation studies to elucidate C fluxes from CWD. Carbon fluxes from decaying CWD can vary considerably due to interspecific and intraspecific differences in composition and different environmental conditions. These variations in C fluxes need to be studied in detail and related to recent advances in soil C sequestration research. Outcomes of this review show that the presence of CWD may enhance the abundance and diversity of the microbial community and constitute additional fluxes of C into the mineral soil by augmented leaching of dissolved organic carbon (DOC). Leached DOC and residues from organic matter (OM) from later decay stages have been shown to be relatively enriched in complex and microbial-derived compounds, which may also be true for CWD-derived OM. Emerging knowledge on soil C stabilization indicates that such complex compounds may be sorbed preferentially to the mineral soil. Moreover, increased abundance and diversity of decomposer organisms may increase the amount of substrate C being diverted into microbial biomass, which may contribute to stable C pools in the forest soil.

Puhlick, J. J., A. R. Weiskittel, I. J. Fernandez, S. Fraver, L. S. Kenefic, R. S. Seymour, R. K. Kolka, L. E. Rustad, and J. C. Brissette. 2016. **Long-term influence of alternative forest management treatments on total ecosystem and wood product carbon storage.** Canadian Journal of Forest Research 46:1404-1412. http://10.1139/cjfr-2016-0193

Abstract. Developing strategies for reducing atmospheric CO_2 is one of the foremost challenges facing natural resource professionals today. The goal of this study was to evaluate total ecosystem and harvested wood product carbon (C) stocks among alternative forest management treatments (selection cutting, shelterwood cutting, commercial clearcutting, and no management) in mixed-species stands in central Maine, USA. These treatments were initiated in the 1950s and have been maintained since, and ecosystem C pools were measured in 2012. When compared across managed treatments, the commercial clearcut had the lowest total ecosystem C stocks by 21%, on average ($P < 0.05$), while the selection and shelterwood treatments had similar total ecosystem C stocks. Including the C stored in harvested wood products did not influence observed differences in C storage among treatments. Total ecosystem C stocks in the reference stand were 247.0 ± 17.7 Mg·ha^{-1} (mean ± SD) compared with 161.7 ± 31.3 Mg·ha^{-1} in the managed stands (171.2 ± 31.7 Mg·ha^{-1} with products C). This study highlights the impacts of long-term forest management treatments on C storage and indicates that the timing of harvests and the species and sizes of trees removed influence C stored in harvested wood products.

Drought

Coats, S., J. E. Smerdon, B. I. Cook, R. Seager, E. R. Cook, and K. J. Anchukaitis. 2016. **Internal ocean-atmosphere variability drives megadroughts in Western North America.** Geophysical Research Letters 43:9886-9894. http://10.1002/2016GL070105

Abstract. Multidecadal droughts that occurred during the Medieval Climate Anomaly represent an important target for validating the ability of climate models to adequately characterize drought risk over the near-term future. A prominent hypothesis is that these megadroughts were driven by a centuries-long radiatively forced shift in the mean state of the tropical Pacific Ocean. Here we use a novel combination of spatiotemporal tree ring reconstructions of Northern

Hemisphere hydroclimate to infer the atmosphere-ocean dynamics that coincide with megadroughts over the American West and find that these features are consistently associated with 10–30 year periods of frequent cold El Niño–Southern Oscillation conditions and not a centuries-long shift in the mean of the tropical Pacific Ocean. These results suggest an important role for internal variability in driving past megadroughts. State-of-the-art climate models from the Coupled Model Intercomparison Project Phase 5, however, do not simulate a consistent association between megadroughts and internal variability of the tropical Pacific Ocean, with implications for our confidence in megadrought risk projections.

Kolb, T. E., C. J. Fettig, M. P. Ayres, B. J. Bentz, J. A. Hicke, R. Mathiasen, J. E. Stewart, and A. S. Weed. 2016. **Observed and anticipated impacts of drought on forest insects and diseases in the United States.** Forest Ecology and Management 380:321-334. http://dx.doi.org/10.1016/j.foreco.2016.04.051

Abstract. Future anthropogenic-induced changes to the earth's climate will likely include increases in temperature and changes in precipitation that will increase the frequency and severity of droughts. Insects and fungal diseases are important disturbances in forests, yet understanding of the role of drought in outbreaks of these agents is limited. Current knowledge concerning the effects of drought on herbivorous insect and pathogen outbreaks in U.S. forests is reviewed, and compared between the relatively mesic and structurally diverse forests of the eastern U.S. and the more xeric forests of the western U.S. Theory and limited evidence suggests a non-linear relationship between drought intensity and outbreaks of aggressive bark beetle species (i.e., those capable of causing extensive levels of tree mortality), where moderate droughts reduce bark beetle population performance and subsequent tree mortality, whereas intense droughts, which frequently occur in the western U.S., increase bark beetle performance and tree mortality. There is little evidence for a role of drought in outbreaks of the southern pine beetle (*Dendroctonus frontalis*), the only bark beetle species that causes large amounts of tree mortality in the eastern U.S. Defoliators do not show consistent responses to drought. The response of sapfeeders to drought appears non-linear, with the greatest performance and impacts at intermediate drought intensity or when drought is alleviated by wetter periods. Interactions between tree pathogens and drought are poorly understood, but available evidence suggests reduced pathogen performance and host impacts in response to drought for primary pathogens and pathogens whose lifecycle depends directly on moisture (humidity). In these cases, rates of reproduction, spread, and infection tend to be greater when conditions are moist. In contrast, secondary fungal pathogens (i.e., those that depend on stressed hosts for colonization) are anticipated to respond to drought with greater performance and host impacts. In the western U.S., drought increases stress on trees severely infected by mistletoes thereby predisposing mistletoe-infected trees to attack by insects, particularly bark beetles and wood borers. Research needed to advance understanding of drought impacts on forest insects and diseases, and the role of forest management in mitigation of infestations during drought are discussed.

Luce, C. H., J. M. Vose, N. Pederson, J. Campbell, C. Millar, P. Kormos, and R. Woods. 2016. **Contributing factors for drought in United States forest ecosystems under projected future climates and their uncertainty.** Forest Ecology and Management 380:299-308. http://dx.doi.org/10.1016/j.foreco.2016.05.020

Abstract. Observations of increasing global forest die-off related to drought are leading to more questions about potential increases in drought occurrence, severity, and ecological consequence in the future. Dry soils and warm temperatures interact to affect trees during drought; so understanding shifting risks requires some understanding of changes in both temperature and precipitation. Unfortunately, strong precipitation uncertainties in climate models yield substantial uncertainty in projections of drought occurrence. We argue that disambiguation of drought effects into temperature and precipitation-mediated processes can alleviate some of the implied uncertainty. In particular, the disambiguation can clarify geographic diversity in forest sensitivity to multifarious drivers of drought and mortality, making more specific use of geographically diverse climate projections. Such a framework may provide forest managers with an easier heuristic in discerning geographically diverse adaptation options. Warming temperatures in the future mean three things with respect to drought in forests: (1) droughts, typically already unusually hot periods, will become hotter, (2) the drying capacity of the air, measured as the vapor pressure deficit (VPD) will become greater, and (3) a smaller fraction of precipitation will fall as snow. More hot-temperature extremes will be more stressful in a direct way to living tissue, and greater VPD will increase pressure gradients within trees, exacerbating the risk of hydraulic failure. Reduced storage in snowpacks reduces summer water availability in some places. Warmer temperatures do

not directly cause drier soils, however. In a hydrologic sense, warmer temperatures do little to cause "drought" as defined by water balances. Instead, much of the future additional longwave energy flux is expected to cause warming rather than evaporating water. Precipitation variations, in contrast, affect water balances and moisture availability directly; so uncertainties in future precipitation generate uncertainty in drought occurrence and severity projections. Although specific projections in annual and seasonal precipitation are uncertain, changes in inter-storm spacing and precipitation type (snow vs. rain) have greater certainty and may have utility in improving spatial projections of drought as perceived by vegetation, a value not currently captured by simple temperature-driven evaporation projections. This review ties different types of future climate shifts to expected consequences for drought and potential influences on physiology, and then explains sources of uncertainty for consideration in future mortality projections. One intention is to provide guidance on partitioning of uncertainty in projections of forest stresses.

MacDonald, G. M., K. A. Moser, A. M. Bloom, A. P. Potito, D. F. Porinchu, J. R. Holmquist, J. Hughes, and K. V. Kremenetski. 2016. **Prolonged California aridity linked to climate warming and Pacific sea surface temperature.** Scientific Reports 6:33325. http://10.1038/srep33325

Abstract. California has experienced a dry 21st century capped by severe drought from 2012 through 2015 prompting questions about hydroclimatic sensitivity to anthropogenic climate change and implications for the future. We address these questions using a Holocene lake sediment record of hydrologic change from the Sierra Nevada Mountains coupled with marine sediment records from the Pacific. These data provide evidence of a persistent relationship between past climate warming, Pacific sea surface temperature (SST) shifts and centennial to millennial episodes of California aridity. The link is most evident during the thermal-maximum of the mid-Holocene (~8 to 3 ka; ka = 1,000 calendar years before present) and during the Medieval Climate Anomaly (MCA) (~1 ka to 0.7 ka). In both cases, climate warming corresponded with cooling of the eastern tropical Pacific despite differences in the factors producing increased radiative forcing. The magnitude of prolonged eastern Pacific cooling was modest, similar to observed La Niña excursions of 1° to 2°C. Given differences with current radiative forcing it remains uncertain if the Pacific will react in a similar manner in the 21st century, but should it follow apparent past behavior more intense and prolonged aridity in California would result.

Mote, P. W., D. E. Rupp, S. Li, D. J. Sharp, F. Otto, P. F. Uhe, M. Xiao, D. P. Lettenmaier, H. Cullen, and M. R. Allen. 2016. **Perspectives on the causes of exceptionally low 2015 snowpack in the western United States.** Geophysical Research Letters 43:10,980-910,988. http://10.1002/2016GL069965

Abstract. Augmenting previous papers about the exceptional 2011–2015 California drought, we offer new perspectives on the “snow drought” that extended into Oregon in 2014 and Washington in 2015. Over 80% of measurement sites west of 115°W experienced record low snowpack in 2015, and we estimate a return period of 400–1000 years for California's snowpack under the questionable assumption of stationarity. Hydrologic modeling supports the conclusion that 2015 was the most severe on record by a wide margin. Using a crowd-sourced superensemble of regional climate model simulations, we show that both human influence and sea surface temperature (SST) anomalies contributed strongly to the risk of snow drought in Oregon and Washington: the contribution of SST anomalies was about twice that of human influence. By contrast, SSTs and humans appear to have played a smaller role in creating California's snow drought. In all three states, the anthropogenic effect on temperature exacerbated the snow drought.

Phillips, R. P., I. Ibáñez, L. D’Orangeville, P. J. Hanson, M. G. Ryan, and N. G. McDowell. 2016. **A belowground perspective on the drought sensitivity of forests: Towards improved understanding and simulation.** Forest Ecology and Management 380:309-320. http://dx.doi.org/10.1016/j.foreco.2016.08.043

Abstract. Predicted increases in the frequency and intensity of droughts across the temperate biome have highlighted the need to examine the extent to which forests may differ in their sensitivity to water stress. At present, a rich body of literature exists on how leaf- and stem-level physiology influence tree drought responses; however, less is known regarding the dynamic interactions that occur belowground between roots and soil physical and biological factors. Hence, there is a need to better understand how and why processes occurring belowground influence forest sensitivity to drought. Here, we review what is known about tree species’ belowground strategies for dealing with drought, and how physical and biological characteristics of soils interact with rooting strategies to influence forest sensitivity to

drought. Then, we highlight how a belowground perspective of drought can be used in models to reduce uncertainty in predicting the ecosystem consequences of droughts in forests. Finally, we describe the challenges and opportunities associated with managing forests under conditions of increasing drought frequency and intensity, and explain how a belowground perspective on drought may facilitate improved forest management.

Swann, A. L. S., F. M. Hoffman, C. D. Koven, and J. T. Randerson. 2016. **Plant responses to increasing CO_2 reduce estimates of climate impacts on drought severity.** Proceedings of the National Academy of Sciences 113:10019-10024. http://10.1073/pnas.1604581113

Abstract. Rising atmospheric CO_2 will make Earth warmer, and many studies have inferred that this warming will cause droughts to become more widespread and severe. However, rising atmospheric CO_2 also modifies stomatal conductance and plant water use, processes that are often are overlooked in impact analysis. We find that plant physiological responses to CO_2 reduce predictions of future drought stress, and that this reduction is captured by using plant-centric rather than atmosphere-centric metrics from Earth system models (ESMs). The atmosphere-centric Palmer Drought Severity Index predicts future increases in drought stress for more than 70% of global land area. This area drops to 37% with the use of precipitation minus evapotranspiration (P-E), a measure that represents the water flux available to downstream ecosystems and humans. The two metrics yield consistent estimates of increasing stress in regions where precipitation decreases are more robust (southern North America, northeastern South America, and southern Europe). The metrics produce diverging estimates elsewhere, with P-E predicting decreasing stress across temperate Asia and central Africa. The differing sensitivity of drought metrics to radiative and physiological aspects of increasing CO_2 partly explains the divergent estimates of future drought reported in recent studies. Further, use of ESM output in offline models may double-count plant feedbacks on relative humidity and other surface variables, leading to overestimates of future stress. The use of drought metrics that account for the response of plant transpiration to changing CO_2, including direct use of P-E and soil moisture from ESMs, is needed to reduce uncertainties in future assessment.

Vose, J. M., C. F. Miniat, C. H. Luce, H. Asbjornsen, P. V. Caldwell, J. L. Campbell, G. E. Grant, D. J. Isaak, S. P. Loheide Ii, and G. Sun. 2016. **Ecohydrological implications of drought for forests in the United States.** Forest Ecology and Management 380:335-345. http://dx.doi.org/10.1016/j.foreco.2016.03.025

Abstract. The relationships among drought, surface water flow, and groundwater recharge are not straightforward for most forest ecosystems due to the strong role that vegetation plays in the forest water balance. Hydrologic responses to drought can be either mitigated or exacerbated by forest vegetation depending upon vegetation water use and how forest population dynamics respond to drought. Understanding how drought impacts ecosystems requires understanding how drought impacts ecohydrological processes. Because different species and functional groups vary in their ecophysiological traits that influence water use patterns, changes in species assemblages can alter hydrological processes from the stand to the watershed scales. Recent warming trends and more prolonged and frequent droughts have accelerated the spread and intensity of insect attacks in the western US that kill nearly all of the canopy trees within forest stands, changing the energy balance of the land surface and affecting many hydrologic processes. In contrast, some eastern forest tree species and size classes can tolerate drought better than others, suggesting the potential for drought-mediated shifts in both species composition and structure. Predicting how these changes will impact hydrologic processes at larger spatial and temporal scales presents a considerable challenge. The biogeochemical consequences of drought, such as changes in stream chemistry, are closely linked to vegetation dynamics and hydrologic responses. As with other natural disturbances, droughts are difficult to prepare for because they are unpredictable. However, there are management options that may be implemented to minimize the impacts of drought on water quantity and quality. Examples include reducing leaf area by thinning and regenerating cut forests with species that consume less water, although a high level of uncertainty in both drought projections and anticipated responses suggests the need for monitoring and adaptive management.

Xiao, M., B. Nijssen, and D. P. Lettenmaier. 2016. **Drought in the Pacific Northwest, 1920–2013.** Journal of Hydrometeorology 17:2391-2404. http://10.1175/jhm-d-15-0142.1

Abstract. The severity–area–duration (SAD) method is used in conjunction with the Variable Infiltration Capacity model (VIC) to identify the major historical total moisture (TM; soil moisture plus snow water equivalent) droughts over the Pacific Northwest region, defined as the Columbia River basin and the region's coastal drainages, for the period 1920–2013. The motivation is to understand how droughts identified using TM (a measure similar to that used in the U.S. Drought Monitor) relate to sector-specific drought measures that are more relevant to users. It is found that most of the SAD space is dominated by an extended drought period during the 1930s, although the most severe shorter droughts are in the 1970s (1976–78) and early 2000s (2000–04). The impact of the three severe TM droughts that dominate most of the SAD space are explored in terms of sector-specific measures relevant to dryland and irrigated agriculture, hydropower generation, municipal water supply, and recreation. It is found that in many cases the most severe droughts identified using the SAD method also appear among the most severe sector-specific droughts; however, there are important exceptions. Two types of inconsistencies are examined and the nature of the conditions that give rise to them are explored.

Phenology Changes

Ford, K. R., C. A. Harrington, S. Bansal, P. J. Gould, and J. B. St. Clair. 2016. **Will changes in phenology track climate change? A study of growth initiation timing in coast Douglas-fir.** Global Change Biology 22:3712-3723. http://10.1111/gcb.13328

Abstract. Under climate change, the reduction of frost risk, onset of warm temperatures and depletion of soil moisture are all likely to occur earlier in the year in many temperate regions. The resilience of tree species will depend on their ability to track these changes in climate with shifts in phenology that lead to earlier growth initiation in the spring. Exposure to warm temperatures ('forcing') typically triggers growth initiation, but many trees also require exposure to cool temperatures ('chilling') while dormant to readily initiate growth in the spring. If warming increases forcing and decreases chilling, climate change could maintain, advance or delay growth initiation phenology relative to the onset of favorable conditions. We modeled the timing of height- and diameter-growth initiation in coast Douglas-fir (an ecologically and economically vital tree in western North America) to determine whether changes in phenology are likely to track changes in climate using data from field-based and controlled-environment studies, which included conditions warmer than those currently

experienced in the tree's range. For high latitude and elevation portions of the tree's range, our models predicted that warming will lead to earlier growth initiation and allow trees to track changes in the onset of the warm but still moist conditions that favor growth, generally without substantially greater exposure to frost. In contrast, toward lower latitude and elevation range limits, the models predicted that warming will lead to delayed growth initiation relative to changes in climate due to reduced chilling, with trees failing to capture favorable conditions in the earlier parts of the spring. This maladaptive response to climate change was more prevalent for diameter-growth initiation than height-growth initiation. The decoupling of growth initiation with the onset of favorable climatic conditions could reduce the resilience of coast Douglas-fir to climate change at the warm edges of its distribution.

Monahan, W. B., A. Rosemartin, K. L. Gerst, N. A. Fisichelli, T. Ault, M. D. Schwartz, J. E. Gross, and J. F. Weltzin. 2016. **Climate change is advancing spring onset across the U.S. national park system.** Ecosphere 7:e01465. http://10.1002/ecs2.1465

Abstract. Many U.S. national parks are already at the extreme warm end of their historical temperature distributions. With rapidly warming conditions, park resource management will be enhanced by information on seasonality of climate that supports adjustments in the timing of activities such as treating invasive species, operating visitor facilities, and scheduling climate-related events (e.g., flower festivals and fall leaf-viewing). Seasonal changes in vegetation, such as pollen, seed, and fruit production, are important drivers of ecological processes in parks, and phenology has thus been identified as a key indicator for park monitoring. Phenology is also one of the most proximate biological responses to climate change. Here, we use estimates of start of spring based on climatically modeled dates of first leaf and first bloom derived from indicator plant species to evaluate the recent timing of spring onset (past 10–30 yr) in each U.S. natural resource park relative to its historical range of variability across the past 112 yr (1901–2012). Of the 276 high latitude to subtropical parks examined, spring is advancing in approximately three-quarters of parks (76%), and 53% of parks are experiencing “extreme” early springs that exceed 95% of historical conditions. Our results demonstrate how changes in climate seasonality are important for understanding ecological responses to climate change, and further how spatial variability in effects of climate change necessitates different approaches to management. We discuss how our results inform climate change adaptation challenges and opportunities facing parks,

with implications for other protected areas, by exploring consequences for resource management and planning.

Species Range Changes

Massie, M. H., T. M. Wilson, A. T. Morzillo, and E. B. Henderson. 2016. **Natural areas as a basis for assessing ecosystem vulnerability to climate change.** Ecosphere 7:e01563. http://10.1002/ecs2.1563

Abstract. There are more than 580 natural areas in Oregon and Washington managed by 20 federal, state, local, and private agencies and organizations. This natural areas network is unparalleled in its representation of the diverse ecosystems found in the Pacific Northwest, and could prove useful for monitoring long-term ecological responses to climate change. Our objectives were to (1) evaluate potential effects of climate change on these natural areas and (2) develop strategies for selecting and prioritizing sites for long-term monitoring. Bioclimatic and Random Forest modeling were used to identify subsets of natural areas to prioritize for long-term monitoring efforts based on the current and projected (2020s, 2050s, 2080s) outputs from 13 future climate models. Projection consensus suggest some of the largest effects of climate change on natural areas may be the result of a substantial range increase in suitable climate for warmer-adapted forest types coupled with a reduction in habitat for cooler-adapted forest types. We identify four strategies that could be used for prioritizing sites and help manage and protect biodiversity in the Pacific Northwest, especially given uncertainty over climate change effects.

Forest Vegetation

Bell, D. M., and A. N. Gray. 2016. **Assessing intra- and inter-regional climate effects on Douglas-fir biomass dynamics in Oregon and Washington, USA.** Forest Ecology and Management 379:281-287. http://dx.doi.org/10.1016/j.foreco.2016.07.023

Abstract. While ecological succession shapes contemporary forest structure and dynamics, other factors like forest structure (dense vs. sparse canopies) and climate may alter structural trajectories. To

assess potential sources of variation in structural trajectories, we examined proportional biomass change for a regionally dominant tree species, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), across vegetation zones representing broad gradients in precipitation and temperature with 3510 forest inventory plots in Oregon and Washington, USA. We found that *P. menziesii* biomass change decreased with *P. menziesii* biomass stocks and increased with *P. menziesii* density, remaining positive in older stands only in the wet and warm vegetation zone. Within two of the vegetation zones, biomass change was greatest in warm and wet environments. In dry vegetation zones, positive *P. menziesii* biomass change responses to initial canopy cover and canopy cover change (i.e., increases with cover loss and decreases with cover gain) indicated shifts in forest structure. Variation in *P. menziesii* biomass dynamics within and between vegetation zones imply multi-scale climatic controls on forest structural trajectories for *P. menziesii* and highlight the potential for continued atmospheric carbon sequestration in warm and wet forests of the Pacific Northwest for both young and old forests, given that future climatic conditions support similar forest dynamics.

Copenhaver-Parry, P. E., and E. Cannon. 2016. **The relative influences of climate and competition on tree growth along montane ecotones in the Rocky Mountains.** Oecologia 182:13-25. http://10.1007/s00442-016-3565-x

Abstract. Distribution shifts of tree species are likely to be highly dependent upon population performance at distribution edges. Understanding the drivers of aspects of performance, such as growth, at distribution edges is thus crucial to accurately predicting responses of tree species to climate change. Here, we use a Bayesian model and sensitivity analysis to partition the effects of climate and crowding, as a metric of competition, on radial growth of three dominant conifer species along montane ecotones in the Rocky Mountains. These ecotones represent upper and lower distribution edges of two species, and span the distribution interior of the third species. Our results indicate a greater influence of climate (i.e., temperature and precipitation) than crowding on radial growth. Competition importance appears to increase towards regions of more favorable growing conditions, and precise responses to crowding and climate vary across species. Overall, our results suggest that climate will likely be the most important determinant of changes in tree growth at distribution edges of these montane conifers in the future.

Das, A. J., N. L. Stephenson, and K. P. Davis. 2016. **Why do trees die? Characterizing the drivers of background tree mortality.** Ecology 97:2616-2627. http://10.1002/ecy.1497

Abstract. The drivers of background tree mortality rates—the typical low rates of tree mortality found in forests in the absence of acute stresses like drought—are central to our understanding of forest dynamics, the effects of ongoing environmental changes on forests, and the causes and consequences of geographical gradients in the nature and strength of biotic interactions. To shed light on factors contributing to background tree mortality, we analyzed detailed pathological data from 200,668 tree-years of observation and 3,729 individual tree deaths, recorded over a 13-yr period in a network of old-growth forest plots in California's Sierra Nevada mountain range. We found that: (1) Biotic mortality factors (mostly insects and pathogens) dominated (58%), particularly in larger trees (86%). Bark beetles were the most prevalent (40%), even though there were no outbreaks during the study period; in contrast, the contribution of defoliators was negligible. (2) Relative occurrences of broad classes of mortality factors (biotic, 58%; suppression, 51%; and mechanical, 25%) are similar among tree taxa, but may vary with tree size and growth rate. (3) We found little evidence of distinct groups of mortality factors that predictably occur together on trees. Our results have at least three sets of implications. First, rather than being driven by abiotic factors such as lightning or windstorms, the "ambient" or "random" background mortality that many forest models presume to be independent of tree growth rate is instead dominated by biotic agents of tree mortality, with potentially critical implications for forecasting future mortality. Mechanistic models of background mortality, even for healthy, rapidly growing trees, must therefore include the insects and pathogens that kill trees. Second, the biotic agents of tree mortality, instead of occurring in a few predictable combinations, may generally act opportunistically and with a relatively large degree of independence from one another. Finally, beyond the current emphasis on folivory and leaf defenses, studies of broad-scale gradients in the nature and strength of biotic interactions should also include biotic attacks on, and defenses of, tree stems and roots.

Johnstone, J. F., C. D. Allen, J. F. Franklin, L. E. Frelich, B. J. Harvey, P. E. Higuera, M. C. Mack, R. K. Meentemeyer, M. R. Metz, G. L. W. Perry, T. Schoennagel, and M. G. Turner. 2016. **Changing disturbance regimes, ecological memory, and forest resilience.** Frontiers in Ecology and the Environment 14:369-378. http://10.1002/fee.1311

Abstract. Ecological memory is central to how ecosystems respond to disturbance and is maintained by two types of legacies – information and material. Species life-history traits represent an adaptive response to disturbance and are an information legacy; in contrast, the abiotic and biotic structures (such as seeds or nutrients) produced by single disturbance events are material legacies. Disturbance characteristics that support or maintain these legacies enhance ecological resilience and maintain a “safe operating space” for ecosystem recovery. However, legacies can be lost or diminished as disturbance regimes and environmental conditions change, generating a “resilience debt” that manifests only after the system is disturbed. Strong effects of ecological memory on post-disturbance dynamics imply that contingencies (effects that cannot be predicted with certainty) of individual disturbances, interactions among disturbances, and climate variability combine to affect ecosystem resilience. We illustrate these concepts and introduce a novel ecosystem resilience framework with examples of forest disturbances, primarily from North America. Identifying legacies that support resilience in a particular ecosystem can help scientists and resource managers anticipate when disturbances may trigger abrupt shifts in forest ecosystems, and when forests are likely to be resilient.

Kline, J. D., M. E. Harmon, T. A. Spies, A. T. Morzillo, R. J. Pabst, B. C. McComb, F. Schnekenburger, K. A. Olsen, B. Csuti, and J. C. Vogeler. 2016. **Evaluating carbon storage, timber harvest, and habitat possibilities for a Western Cascades (USA) forest landscape.** Ecological Applications 26:2044-2059. http://10.1002/eap.1358

Abstract. Forest policymakers and managers have long sought ways to evaluate the capability of forest landscapes to jointly produce timber, habitat, and other ecosystem services in response to forest management. Currently, carbon is of particular interest as policies for increasing carbon storage on federal lands are being proposed. However, a challenge in joint production analysis of forest management is adequately representing ecological conditions and processes that influence joint production relationships. We used simulation models of vegetation structure, forest sector carbon, and potential wildlife habitat to characterize landscape-level joint production possibilities for carbon storage, timber harvest, and habitat for seven wildlife species across a range of forest management regimes. We sought to (1) characterize the general relationships of production possibilities for combinations of carbon storage, timber, and habitat, and (2) identify management variables that most influence joint production relationships. Our 160 000-ha study landscape featured environmental conditions typical of forests in the Western Cascade Mountains of Oregon (USA). Our results indicate that managing forests for carbon storage involves trade-offs among timber harvest and habitat for focal wildlife species, depending on the disturbance interval and utilization intensity followed. Joint production possibilities for wildlife species varied in shape, ranging from competitive to complementary to compound, reflecting niche breadth and habitat component needs of species examined. Managing Pacific Northwest forests to store forest sector carbon can be roughly complementary with habitat for Northern Spotted Owl, Olive-sided Flycatcher, and red tree vole. However, managing forests to increase carbon storage potentially can be competitive with timber production and habitat for Pacific marten, Pileated Woodpecker, and Western Bluebird, depending on the disturbance interval and harvest intensity chosen. Our analysis suggests that joint production possibilities under forest management regimes currently typical on industrial forest lands (e.g., 40- to 80-yr rotations with some tree retention for wildlife) represent but a small fraction of joint production outcomes possible in the region. Although the theoretical boundaries of the production possibilities sets we developed are probably unachievable in the current management environment, they arguably define the long-term potential of managing forests to produce multiple ecosystem services within and across multiple forest ownerships.

Koenig, W. D., R. Alejano, M. D. Carbonero, P. Fernández-Rebollo, J. M. H. Knops, T. Marañón, C. M. Padilla-Díaz, I. S. Pearse, I. M. Pérez-Ramos, J. Vázquez-Piqué, and M. B. Pesendorfer. 2016. **Is the relationship between mast-seeding and weather in oaks related to their life-history or phylogeny?** Ecology 97:2603-2615. http://10.1002/ecy.1490

Abstract. Although the functional basis of variable and synchronous seed production (masting behavior) has been extensively investigated, only recently has attention been focused on the proximate mechanisms driving this phenomenon. We analyzed the relationship between weather and acorn production in 15 species of oaks (genus

Quercus) from three geographic regions on two continents, with the goals of determining the extent to which similar sets of weather factors affect masting behavior across species and to explore the ecological basis for the similarities detected. Lag-1 temporal autocorrelations were predominantly negative, supporting the hypothesis that stored resources play a role in masting behavior across this genus, and we were able to determine environmental variables correlating with acorn production in all but one of the species. Standard weather variables outperformed "differential-cue" variables based on the difference between successive years in a majority of species, which is consistent with the hypothesis that weather is linked directly to the proximate mechanism driving seed production and that masting in these species is likely to be sensitive to climate change. Based on the correlations between weather variables and acorn production, cluster analysis failed to generate any obvious groups of species corresponding to phylogeny or life-history. Discriminant function analyses, however, were able to identify the phylogenetic section to which the species belonged and, controlling for phylogeny, the length of time species required to mature acorns, whether they were evergreen or deciduous, and, to a lesser extent, the geographic region to which they are endemic. These results indicate that similar proximate mechanisms are driving acorn production in these species of oaks, that the environmental factors driving seed production in oaks are to some extent phylogenetically conserved, and that the shared mechanisms driving acorn production result in some degree of synchrony among coexisting species in a way that potentially enhances predator satiation, at least when they have acorns requiring the same length of time to mature.

Sohn, J. A., S. Saha, and J. Bauhus. 2016. **Potential of forest thinning to mitigate drought stress: A meta-analysis.** Forest Ecology and Management 380:261-273. http://dx.doi.org/10.1016/j.foreco.2016.07.046

Abstract. Increasing frequency of extremely dry and hot summers in some regions emphasise the need for silvicultural approaches to increase the drought tolerance of existing forests in the short term, before long-term adaptation through species changes may be possible. The aim of this meta-analysis was to assess the potential of thinning for improving tree performance during and after drought. We used results from 23 experiments that employed different thinning intensities including an unthinned control and focused on the response variables: radial growth, carbon- and oxygen-isotopes in tree-rings and pre-dawn leaf-water potential. We found that thinning effects on

the growth response to drought differed between broadleaves and conifers, although these findings are based on few studies only in broadleaved forests. Thinning helped to mitigate growth reductions during drought in broadleaves, most likely via increases of soil water availability. In contrast, in conifers, comparable drought-related growth reductions and increases of water-use efficiency were observed in all treatments but thinning improved the post-drought recovery and resilience of radial growth. Results of meta-regression analysis indicate that benefits of both moderate and heavy thinning for growth performance following drought (recovery and resilience) decrease with time since the last intervention. Further, growth resistance during drought became smaller with stand age while the rate of growth recovery following drought increased over time irrespective of treatment. Heavy but not moderate thinning helped to avoid an age-related decline in medium-term growth resilience to drought. For both closed and very open stands, growth performance during drought improved with increasing site aridity but for the same stands growth recovery and resilience following drought was reduced with increasing site aridity. This synthesis of experiments from a wide geographical range has demonstrated that thinning, in particular heavy thinning, is a suitable approach to improve the growth response of remaining trees to drought in both conifers and broadleaves but the underlying processes differ and need to be considered.

Rangeland Vegetation

Holthuijzen, M. F., and K. E. Veblen. 2016. **Grazing effects on precipitation-driven associations between sagebrush and perennial grasses.** Western North American Naturalist 76:313-325. http://10.3398/064.076.0308

Abstract. While many studies have addressed the effect of individual stresses on plant—plant associations, few have addressed the effects of co-occurring stresses. We therefore investigated how associations between Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) and 2 native grasses (*Poa secunda* and *Elymus elymoides*) responded to different combinations of grazing and moisture stresses in the Great Basin, USA. Positive (i.e., facilitative) interactions between nurse plants and their beneficiaries are predicted to increase with increasing moisture limitation and grazing stress, but these interactions may break down at extreme levels of stress. We hypothesized that (1) competitive interactions and negative shrub-

grass spatial associations would occur under the least stressful conditions (low grazing intensity / high precipitation); (2) positive shrub-grass spatial associations would dominate at intermediate levels of stress (high grazing intensity / high precipitation and low grazing intensity / low precipitation); and (3) negative grass-shrub relationships would dominate at extreme levels of stress (high grazing / low precipitation). We sampled 5 site pairs (high vs. low grazing intensity) that occurred over a precipitation gradient. We assessed how abundance of the 2 grasses *P. secunda* and *E. elymoides* responded to sagebrush microsite (canopy vs. interspace), grazing intensity, and precipitation. We found that both grass species were positively associated with A. tridentata canopy microsites at low annual precipitation levels. However, grazing stress appeared to weaken this effect for *P. secunda*, indicating, as we predicted, a potential breakdown of facilitative interactions in highly stressful conditions. Although we predicted that facilitation would dominate in moderately stressful conditions, we only found this to be true (for both grasses) in one of the 2 moderately stressful scenarios (low grazing / low precipitation). Our results provide insights into how Great Basin plant communities may respond to the separate and combined effects of grazing and drought stresses, both of which may intensify in the future.

Palmquist, K. A., D. R. Schlaepfer, J. B. Bradford, and W. K. Lauenroth. 2016. **Mid-latitude shrub steppe plant communities: climate change consequences for soil water resources.** Ecology 97:2342-2354. http://10.1002/ecy.1457

Abstract. In the coming century, climate change is projected to impact precipitation and temperature regimes worldwide, with especially large effects in drylands. We use big sagebrush ecosystems as a model dryland ecosystem to explore the impacts of altered climate on ecohydrology and the implications of those changes for big sagebrush plant communities using output from 10 Global Circulation Models (GCMs) for two representative concentration pathways (RCPs). We ask: (1) What is the magnitude of variability in future temperature and precipitation regimes among GCMs and RCPs for big sagebrush ecosystems, and (2) How will altered climate and uncertainty in climate forecasts influence key aspects of big sagebrush water balance? We explored these questions across 1980–2010, 2030–2060, and 2070–2100 to determine how changes in water balance might develop through the 21st century. We assessed ecohydrological variables at 898 sagebrush sites across the western US using a process-based soil water model, SOILWAT, to model all components of

daily water balance using site-specific vegetation parameters and site-specific soil properties for multiple soil layers. Our modeling approach allowed for changes in vegetation based on climate. Temperature increased across all GCMs and RCPs, whereas changes in precipitation were more variable across GCMs. Winter and spring precipitation was predicted to increase in the future (7% by 2030–2060, 12% by 2070–2100), resulting in slight increases in soil water potential (SWP) in winter. Despite wetter winter soil conditions, SWP decreased in late spring and summer due to increased evapotranspiration (6% by 2030–2060, 10% by 2070–2100) and groundwater recharge (26% and 30% increase by 2030–2060 and 2070–2100). Thus, despite increased precipitation in the cold season, soils may dry out earlier in the year, resulting in potentially longer, drier summer conditions. If winter precipitation cannot offset drier summer conditions in the future, we expect big sagebrush regeneration and survival will be negatively impacted, potentially resulting in shifts in the relative abundance of big sagebrush plant functional groups. Our results also highlight the importance of assessing multiple GCMs to understand the range of climate change outcomes on ecohydrology, which was contingent on the GCM chosen.

Tredennick, A. T., M. B. Hooten, C. L. Aldridge, C. G. Homer, A. R. Kleinhesselink, and P. B. Adler. 2016. **Forecasting climate change impacts on plant populations over large spatial extents.** Ecosphere 7:e01525. http://10.1002/ecs2.1525

Abstract. Plant population models are powerful tools for predicting climate change impacts in one location, but are difficult to apply at landscape scales. We overcome this limitation by taking advantage of two recent advances: remotely sensed, species-specific estimates of plant cover and statistical models developed for spatiotemporal dynamics of animal populations. Using computationally efficient model reparameterizations, we fit a spatiotemporal population model to a 28-year time series of sagebrush (*Artemisia* spp.) percent cover over a 2.5 × 5 km landscape in southwestern Wyoming while formally accounting for spatial autocorrelation. We include interannual variation in precipitation and temperature as covariates in the model to investigate how climate affects the cover of sagebrush. We then use the model to forecast the future abundance of sagebrush at the landscape scale under projected climate change, generating spatially explicit estimates of sagebrush population trajectories that have, until now, been impossible to produce at this scale. Our broadscale and long-term predictions are rooted in small-scale and short-term population dynamics and provide an alternative to predictions offered

by species distribution models that do not include population dynamics. Our approach, which combines several existing techniques in a novel way, demonstrates the use of remote sensing data to model population responses to environmental change that play out at spatial scales far greater than the traditional field study plot.

Zhu, K., N. R. Chiariello, T. Tobeck, T. Fukami, and C. B. Field. 2016. **Nonlinear, interacting responses to climate limit grassland production under global change.** Proceedings of the National Academy of Sciences 113:10589-10594. http://10.1073/pnas.1606734113

Abstract. Global changes in climate, atmospheric composition, and pollutants are altering ecosystems and the goods and services they provide. Among approaches for predicting ecosystem responses, long-term observations and manipulative experiments can be powerful approaches for resolving single-factor and interactive effects of global changes on key metrics such as net primary production (NPP). Here we combine both approaches, developing multidimensional response surfaces for NPP based on the longest-running, best-replicated, most-multifactor global-change experiment at the ecosystem scale—a 17-y study of California grassland exposed to full-factorial warming, added precipitation, elevated CO_2, and nitrogen deposition. Single-factor and interactive effects were not time-dependent, enabling us to analyze each year as a separate realization of the experiment and extract NPP as a continuous function of global-change factors. We found a ridge-shaped response surface in which NPP is humped (unimodal) in response to temperature and precipitation when CO_2 and nitrogen are ambient, with peak NPP rising under elevated CO_2 or nitrogen but also shifting to lower temperatures. Our results suggest that future climate change will push this ecosystem away from conditions that maximize NPP, but with large year-to-year variability.

Invasive Species

Allen, J. M., and B. A. Bradley. 2016. **Out of the weeds? Reduced plant invasion risk with climate change in the continental United States.** Biological Conservation 203:306-312. http://dx.doi.org/10.1016/j.biocon.2016.09.015

Abstract. Identifying invasion risk is critical for regional prioritization of management and monitoring, however, we currently lack a

comprehensive assessment of the invasion risk posed by plants for the United States. We aim to quantify geographic invasion risk for currently established terrestrial invasive plants in the continental U.S. under current and future climate. We assembled a comprehensive occurrence database for 896 terrestrial invasive plant species from 33 regional collections of field and museum data and projected species ranges using MaxEnt species distribution models based on current (1950–2000 average) and future (2040–2060 average) climate. We quantified geographic invasion risk as differences in species richness, invasion debt, range infilling, and identification of hotspots. Potential invasive plant richness was higher than observed richness, particularly in eastern temperate forests, where as many as 83% of species with suitable climate have not yet established. A small percentage (median = 0.22%) of species' potential ranges are currently occupied by them. With climate change, potential invasive plant richness declined by a median of 7.3% by 2050. About 80% of invasive plant hotspots were geographically stable with climate change, with the remaining 20% shifting northward. Invasion hotspots and current invasion debt reveal extensive, ongoing risk from existing invasive plants across the U.S., particularly in the Southeast. Climate change alters the spatial distributions of focal species for monitoring and is likely to reduce overall invasion risk in many areas. Early detection and rapid response programs could be most effective in stemming the spread of invasive plant species in areas with increased risk under climate change, while areas with persistent high risk are candidates for containment and control. The areas with reduced risk are prime locations for invasion of new imports from tropical and subtropical climates, highlighting the simultaneous need for prevention strategies.

Blumenthal, D. M., J. A. Kray, W. Ortmans, L. H. Ziska, and E. Pendall. 2016. **Cheatgrass is favored by warming but not CO_2 enrichment in a semi-arid grassland.** Global Change Biology 22:3026-3038. http://10.1111/gcb.13278

Abstract. Elevated CO_2 and warming may alter terrestrial ecosystems by promoting invasive plants with strong community and ecosystem impacts. Invasive plant responses to elevated CO_2 and warming are difficult to predict, however, because of the many mechanisms involved, including modification of phenology, physiology, and cycling of nitrogen and water. Understanding the relative and interactive importance of these processes requires multifactor experiments under realistic field conditions. Here, we test how free-air CO_2 enrichment (to 600 ppmv) and infrared warming (+1.5 °C day/3 °C night) influence a functionally and phenologically distinct invasive plant in semi-arid

mixed-grass prairie. *Bromus tectorum* (cheatgrass), a fast-growing Eurasian winter annual grass, increases fire frequency and reduces biological diversity across millions of hectares in western North America. Across 2 years, we found that warming more than tripled *B. tectorum* biomass and seed production, due to a combination of increased recruitment and increased growth. These results were observed with and without competition from native species, under wet and dry conditions (corresponding with tenfold differences in *B. tectorum* biomass), and despite the fact that warming reduced soil water. In contrast, elevated CO_2 had little effect on *B. tectorum* invasion or soil water, while reducing soil and plant nitrogen (N). We conclude that (1) warming may expand *B. tectorum's* phenological niche, allowing it to more successfully colonize the extensive, invasion-resistant northern mixed-grass prairie, and (2) in ecosystems where elevated CO_2 decreases N availability, CO_2 may have limited effects on *B. tectorum* and other nitrophilic invasive species.

Brummer, T. J., K. T. Taylor, J. Rotella, B. D. Maxwell, L. J. Rew, and M. Lavin. 2016. **Drivers of Bromus tectorum abundance in the western North American sagebrush steppe.** Ecosystems 19:986-1000. http://10.1007/s10021-016-9980-3

Abstract. *Bromus tectorum* can transform ecosystems causing negative impacts on the ecological and economic values of sagebrush steppe of the western USA. Although our knowledge of the drivers of the regional distribution of *B. tectorum* has improved, we have yet to determine the relative importance of climate and local factors causing *B. tectorum* abundance and impact. To address this, we sampled 555 sites distributed geographically and ecologically throughout the sagebrush steppe. We recorded the canopy cover of *B. tectorum*, as well as local substrate and vegetation characteristics. Boosted regression tree modeling revealed that climate strongly limits the transformative ability of *B. tectorum* to a portion of the sagebrush steppe with dry summers (that is, July precipitation <10 mm and the driest annual quarter associated with a mean temperature >15°C) and low native grass canopy cover. This portion includes the Bonneville, Columbia, Lahontan, and lower Snake River basins. These areas are likely to require extreme efforts to reverse *B. tectorum* transformation. Our predictions, using future climate conditions, suggest that the transformative ability of *B. tectorum* may not expand geographically and could remain within the same climatically suitable basins. We found *B. tectorum* in locally disturbed areas within or adjacent to all of our sample sites, but not necessarily within sagebrush steppe vegetation. Conversion of the sagebrush steppe by *B. tectorum*,

therefore, is more likely to occur outside the confines of its current climatically optimal region because of site-specific disturbances, including invasive species control efforts and sagebrush steppe mismanagement, rather than climate change.

Mummey, D. L., M. E. Herget, K. M. Hufford, and L. Shreading. 2016. **Germination timing and seedling growth of *Poa secunda* and the invasive grass, *Bromus tectorum*, in response to temperature: evaluating biotypes for seedling traits that improve establishment.** Ecological Restoration 34:200-208. http://10.3368/er.34.3.200

Abstract. Cold temperature seed germination and rapid root growth influence the ability of native plants to establish in the presence of invasive winter annuals. This represents a potential problem for plant material selection in the face of climate change. If seeds sourced from cold winter climates germinate and grow rapidly early in the season, managers that select materials from warmer winter climates could miss populations with traits that promote competitive establishment at restoration sites. We examined seed germination timing and seedling growth rates of the exotic grass, *Bromus tectorum*, two wild-collected *Poa secunda* accessions, and four commercial *P. secunda* accessions under two temperature regimes (20°C day/15°C night and 10°C day/5°C night) to examine the mechanisms responsible for differences in establishment and survivorship between *P. secunda* accessions observed in a previous field study. Our results show that *B. tectorum* had earlier germination, faster root elongation, and greater total root growth than all *P. secunda* accessions in both temperature regimes. Wild-collected *P. secunda* accessions germinated later and had slower cold temperature growth rates than most commercial accessions. *Poa secunda* accessions sourced from areas with colder winter climates germinated earlier and had greater total root length in the cold temperature treatment, suggesting that source location climate can be used to select plant materials with traits beneficial for seedling establishment and tolerance of invasive winter annuals.

Fish and Wildlife

Balzotti, C. S., S. G. Kitchen, and C. McCarthy. 2016. **Beyond the single species climate envelope: a multifaceted approach to mapping climate change vulnerability.** Ecosphere 7:e01444. http://10.1002/ecs2.1444

Abstract. Federal land management agencies and conservation organizations have begun incorporating climate change vulnerability assessments (CCVAs) as an important component in the management and conservation of landscapes. It is often a challenge to translate that knowledge into management plans and actions, even when research infers species risk. Predictive maps can improve current CCVAs and assist in quantifying and visualizing species climate change vulnerability across large areas. We assessed the climate change risk for Greater Sage-Grouse (*Centrocercus urophasianus*; sage-grouse) habitat at two spatial scales in Utah and Nevada. At the local scale, multiple species climate envelopes were evaluated with additional stressors (fire, conifer encroachment, invasive grass, and human impact) to create risk maps for mesic (Strawberry) and xeric (Sheeprock) sage-grouse landscapes in Utah. Both landscapes were predicted to be at risk, but Sheeprock was found to be at higher risk due to future climate change implications coupled with additional habitat-degrading stressors. By using models, we are able to integrate complex interactions, and visualize the distribution of risk across broad spatial scales, providing land managers and researchers a valuable tool for CCVA and action plans.

Hall, L. E., A. D. Chalfoun, E. A. Beever, and A. E. Loosen. 2016. **Microrefuges and the occurrence of thermal specialists: implications for wildlife persistence amidst changing temperatures.** Climate Change Responses 3:8. http://10.1186/s40665-016-0021-4

Abstract. Background. Contemporary climate change is affecting nearly all biomes, causing shifts in animal distributions, phenology, and persistence. Favorable microclimates may buffer organisms against rapid changes in climate, thereby allowing time for populations to adapt. The degree to which microclimates facilitate the local persistence of climate-sensitive species, however, is largely an open question. We addressed the importance of microrefuges in mammalian thermal specialists, using the American pika (*Ochotona princeps*) as a model organism. Pikas are sensitive to ambient temperatures, and are active year-round in the alpine where conditions are highly variable.

We tested four hypotheses about the relationship between microrefuges and pika occurrence: 1) Local-habitat Hypothesis (local-habitat conditions are paramount, regardless of microrefuge); 2) Surface-temperature Hypothesis (surrounding temperatures, unmoderated by microrefuge, best predict occurrence); 3) Interstitial-temperature Hypothesis (temperatures within microrefuges best predict occurrence), and 4) Microrefuge Hypothesis (the degree to which microrefuges moderate the surrounding temperature facilitates occurrence, regardless of other habitat characteristics). We examined pika occurrence at 146 sites across an elevational gradient. We quantified pika presence, physiographic habitat characteristics and forage availability at each site, and deployed paired temperature loggers at a subset of sites to measure surface and subterranean temperatures.

Results. We found strong support for the Microrefuge Hypothesis. Pikas were more likely to occur at sites where the subsurface environment substantially moderated surface temperatures, especially during the warm season. Microrefugium was the strongest predictor of pika occurrence, independent of other critical habitat characteristics, such as forage availability.

Conclusions. By modulating surface temperatures, microrefuges may strongly influence where temperature-limited animals persist in rapidly warming environments. As climate change continues to manifest, efforts to understand the changing dynamics of animal-habitat relationships will be enhanced by considering the quality of microrefuges.

Nadeau, C. P., and A. K. Fuller. 2016. **Combining landscape variables and species traits can improve the utility of climate change vulnerability assessments.** Biological Conservation 202:30-38. http://dx.doi.org/10.1016/j.biocon.2016.07.030

Abstract. Conservation organizations worldwide are investing in climate change vulnerability assessments. Most vulnerability assessment methods focus on either landscape features or species traits that can affect a species vulnerability to climate change. However, landscape features and species traits likely interact to affect vulnerability. We compare a landscape-based assessment, a trait-based assessment, and an assessment that combines landscape variables and species traits for 113 species of birds, herpetofauna, and mammals in the northeastern United States. Our aim is to better understand which species traits and landscape variables have the

largest influence on assessment results and which types of vulnerability assessments are most useful for different objectives. Species traits were most important for determining which species will be most vulnerable to climate change. The sensitivity of species to dispersal barriers and the species average natal dispersal distance were the most important traits. Landscape features were most important for determining where species will be most vulnerable because species were most vulnerable in areas where multiple landscape features combined to increase vulnerability, regardless of species traits. The interaction between landscape variables and species traits was important when determining how to reduce climate change vulnerability. For example, an assessment that combines information on landscape connectivity, climate change velocity, and natal dispersal distance suggests that increasing landscape connectivity may not reduce the vulnerability of many species. Assessments that include landscape features and species traits will likely be most useful in guiding conservation under climate change.

Sears, M. W., M. J. Angilletta, M. S. Schuler, J. Borchert, K. F. Dilliplane, M. Stegman, T. W. Rusch, and W. A. Mitchell. 2016. **Configuration of the thermal landscape determines thermoregulatory performance of ectotherms.** Proceedings of the National Academy of Sciences 113:10595-10600. http://10.1073/pnas.1604824113

Abstract. Although most organisms thermoregulate behaviorally, biologists still cannot easily predict whether mobile animals will thermoregulate in natural environments. Current models fail because they ignore how the spatial distribution of thermal resources constrains thermoregulatory performance over space and time. To overcome this limitation, we modeled the spatially explicit movements of animals constrained by access to thermal resources. Our models predict that ectotherms thermoregulate more accurately when thermal resources are dispersed throughout space than when these resources are clumped. This prediction was supported by thermoregulatory behaviors of lizards in outdoor arenas with known distributions of environmental temperatures. Further, simulations showed how the spatial structure of the landscape qualitatively affects responses of animals to climate. Biologists will need spatially explicit models to predict impacts of climate change on local scales.

Soils and Hydrology

Archfield, S. A., R. M. Hirsch, A. Viglione, and G. Blöschl. 2016. **Fragmented patterns of flood change across the United States.** Geophysical Research Letters 43:10,232-210,239. http://10.1002/2016GL070590

Abstract. Trends in the peak magnitude, frequency, duration, and volume of frequent floods (floods occurring at an average of two events per year relative to a base period) across the United States show large changes; however, few trends are found to be statistically significant. The multidimensional behavior of flood change across the United States can be described by four distinct groups, with streamgages experiencing (1) minimal change, (2) increasing frequency, (3) decreasing frequency, or (4) increases in all flood properties. Yet group membership shows only weak geographic cohesion. Lack of geographic cohesion is further demonstrated by weak correlations between the temporal patterns of flood change and large-scale climate indices. These findings reveal a complex, fragmented pattern of flood change that, therefore, clouds the ability to make meaningful generalizations about flood change across the United States.

Bresciani, E., P. Goderniaux, and O. Batelaan. 2016. **Hydrogeological controls of water table-land surface interactions.** Geophysical Research Letters 43:9653-9661. http://10.1002/2016GL070618

Abstract. Interactions of the water table with the land surface impact a wide range of hydrologic, climatic, ecologic, and geomorphologic processes. Yet the factors controlling these interactions are still poorly understood. In this work, a new 2-D (cross-sectional) analytical groundwater flow solution is used to derive a dimensionless criterion that expresses the conditions under which the water table “outcrops” (i.e., reaches the land surface). The criterion gives insights into the functional relationships between geology, topography, climate, and resulting water table outcrops. This sheds light on the debate about the topographic control of groundwater flow, as the effective role of the topography is to constrain the water table only where it outcrops. The criterion provides a practical tool to predict water table outcrops if physical parameters are known and to estimate physical parameters if on the contrary water table outcrops are known. The latter aspect is demonstrated through an application example.

Palmquist, K. A., D. R. Schlaepfer, J. B. Bradford, and W. K. Lauenroth. 2016. **Spatial and ecological variation in dryland ecohydrological responses to climate change: implications for management.** Ecosphere 7:e01590. http://10.1002/ecs2.1590

Abstract. Ecohydrological responses to climate change will exhibit spatial variability and understanding the spatial pattern of ecological impacts is critical from a land management perspective. To quantify climate change impacts on spatial patterns of ecohydrology across shrub steppe ecosystems in North America, we asked the following question: How will climate change impacts on ecohydrology differ in magnitude and variability across climatic gradients, among three big sagebrush ecosystems (SB-Shrubland, SB-Steppe, SB-Montane), and among Sage-grouse Management Zones? We explored these potential changes for mid-century for RCP8.5 using a process-based water balance model (SOILWAT) for 898 big sagebrush sites using site- and scenario-specific inputs. We summarize changes in available soil water (ASW) and dry days, as these ecohydrological variables may be helpful in guiding land management decisions about where to geographically concentrate climate change mitigation and adaptation resources. Our results suggest that during spring, soils will be wetter in the future across the western United States, while soils will be drier in the summer. The magnitude of those predictions differed depending on geographic position and the ecosystem in question: Larger increases in mean daily spring ASW were expected for high-elevation SB-Montane sites and the eastern and central portions of our study area. The largest decreases in mean daily summer ASW were projected for warm, dry, mid-elevation SB-Montane sites in the central and west-central portions of our study area (decreases of up to 50%). Consistent with declining summer ASW, the number of dry days was projected to increase rangewide, but particularly for SB-Montane and SB-Steppe sites in the eastern and northern regions. Collectively, these results suggest that most sites will be drier in the future during the summer, but changes were especially large for mid- to high-elevation sites in the northern half of our study area. Drier summer conditions in high-elevation, SB-Montane sites may result in increased habitat suitability for big sagebrush, while those same changes will likely reduce habitat suitability for drier ecosystems. Our work has important implications for where land managers should prioritize resources for the conservation of North American shrub steppe plant communities and the species that depend on them.

Fire

Flatley, W. T., and P. Z. Fulé. 2016. **Are historical fire regimes compatible with future climate? Implications for forest restoration.** Ecosphere 7:e01471. http://10.1002/ecs2.1471

Abstract. The restoration of historical fire regimes is often a primary objective in the conservation of fire-adapted forests. However, individual species' responses to future climate change may uncouple historical vegetation–disturbance relationships, producing potentially negative ecological consequences to fire restoration. We used a landscape simulation model to assess how forest pattern will respond to future climate regimes and whether the restoration of historical fire regimes will benefit forest conservation under future climate regimes. Our study landscape was the 335,000-ha Kaibab Plateau at the North Rim of the Grand Canyon spanning a broad elevation-vegetation gradient of pinyon-juniper, ponderosa pine, mixed conifer, and spruce-fir forests along with a range of associated fire regimes. We employed a novel multimodel landscape simulation approach using the Climate-Forest Vegetation Simulator to estimate individual tree species climate responses and LANDIS-II to simulate spatial patterns of fire disturbance, forest growth, regeneration, succession, and dispersal. Model simulations included three climate scenarios (no change, moderate change, and high change) and two fire scenarios (fire exclusion and fire restoration). The climate change scenarios produced declines in mean forest aboveground biomass (AGB) and a compositional turnover equal to one or two vegetation zones, approximating the vegetation displacement that occurred in this location during the Holocene. Fire restoration resulted in earlier, but roughly equivalent, AGB declines and compositional change. Uphill species migration in some elevation zones produced tree species–fire regime mismatches that promoted state changes and increased nonforest area. Regardless of fire management approach, our simulations project that the Kaibab Plateau will eventually be dominated by pinyon–juniper, oak, and ponderosa pine forest types, with a complete loss of mesic conifer species. Our results indicate that fire managers will have to be flexible with the application of historical fire regimes to avoid regeneration failures and abrupt declines in biomass.

Riley, K. L., and R. A. Loehman. 2016. **Mid-21st-century climate changes increase predicted fire occurrence and fire season length, Northern Rocky Mountains, United States.** Ecosphere 7:e01543. http://10.1002/ecs2.1543

Abstract. Climate changes are expected to increase fire frequency, fire season length, and cumulative area burned in the western United States. We focus on the potential impact of mid-21st-century climate changes on annual burn probability, fire season length, and large fire characteristics including number and size for a study area in the Northern Rocky Mountains. Although large fires are rare they account for most of the area burned in western North America, burn under extreme weather conditions, and exhibit behaviors that preclude methods of direct control. Allocation of resources, development of management plans, and assessment of fire effects on ecosystems all require an understanding of when and where fires are likely to burn, particularly under altered climate regimes that may increase large fire occurrence. We used the large fire simulation model FSim to model ignition, growth, and containment of wildfires under two climate scenarios: contemporary (based on instrumental weather) and mid-century (based on an ensemble average of global climate models driven by the A1B SRES emissions scenario). Modeled changes in fire patterns include increased annual burn probability, particularly in areas of the study region with relatively short contemporary fire return intervals; increased individual fire size and annual area burned; and fewer years without large fires. High fire danger days, represented by threshold values of Energy Release Component (ERC), are projected to increase in number, especially in spring and fall, lengthening the climatic fire season. For fire managers, ERC is an indicator of fire intensity potential and fire economics, with higher ERC thresholds often associated with larger, more expensive fires. Longer periods of elevated ERC may significantly increase the cost and complexity of fire management activities, requiring new strategies to maintain desired ecological conditions and limit fire risk. Increased fire activity (within the historical range of frequency and severity, and depending on the extent to which ecosystems are adapted) may maintain or restore ecosystem functionality; however, in areas that are highly departed from historical fire regimes or where there is disequilibrium between climate and vegetation, ecosystems may be rapidly and persistently altered by wildfires, especially those that burn under extreme conditions.

Stevens-Rumann, C., and P. Morgan. 2016. **Repeated wildfires alter forest recovery of mixed-conifer ecosystems.** Ecological Applications 26:1842-1853. http://10.1890/15-1521.1

Abstract. Most models project warmer and drier climates that will contribute to larger and more frequent wildfires. However, it remains unknown how repeated wildfires alter post-fire successional patterns and forest structure. Here, we test the hypothesis that the number of wildfires, as well as the order and severity of wildfire events interact to alter forest structure and vegetation recovery and implications for vegetation management. In 2014, we examined forest structure, composition, and tree regeneration in stands that burned 1–18 yr before a subsequent 2007 wildfire. Three important findings emerged: (1) Repeatedly burned forests had 15% less woody surface fuels and 31% lower tree seedling densities compared with forests that only experienced one recent wildfire. These repeatedly burned areas are recovering differently than sites burned once, which may lead to alternative ecosystem structure. (2) Order of burn severity (high followed by low severity compared with low followed by high severity) did influence forest characteristics. When low burn severity followed high, forests had 60% lower canopy closure and total basal area with 92% fewer tree seedlings than when high burn severity followed low. (3) Time between fires had no effect on most variables measured following the second fire except large woody fuels, canopy closure and tree seedling density. We conclude that repeatedly burned areas meet many vegetation management objectives of reduced fuel loads and moderate tree seedling densities. These differences in forest structure, composition, and tree regeneration have implications not only for the trajectories of these forests, but may reduce fire intensity and burn severity of subsequent wildfires and may be used in conjunction with future fire suppression tactics.

Social and Economics

Norton-Smith, K., K. Lynn, K. Chief, K. Cozzetto, J. Donatuto, M. Hiza Redsteer, L.E. Kruger, J. Maldonado, C. Viles, K.P. Whyte. 2016. **Climate change and indigenous peoples: a synthesis of current impacts and experiences.** Gen. Tech. Rep. PNWGTR-944. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 136 p. Available at: http://www.fs.fed.us/pnw/pubs/pnw_gtr944.pdf

Abstract. A growing body of literature examines the vulnerability, risk, resilience, and adaptation of indigenous peoples to climate change. This synthesis of literature brings together research pertaining to the impacts of climate change on sovereignty, culture, health, and economies that are currently being experienced by Alaska Native and American Indian tribes and other indigenous communities in the United States. The knowledge and science of how climate change impacts are affecting indigenous peoples contributes to the development of policies, plans, and programs for adapting to climate change and reducing greenhouse gas emissions. This report defines and describes the key frameworks that inform indigenous understandings of climate change impacts and pathways for adaptation and mitigation, namely, tribal sovereignty and self-determination, culture and cultural identity, and indigenous community health indicators. It also provides a comprehensive synthesis of climate knowledge, science, and strategies that indigenous communities are exploring, as well as an understanding of the gaps in research on these issues. This literature synthesis is intended to make a contribution to future efforts such as the 4th National Climate Assessment, while serving as a resource for future research, tribal and agency climate initiatives, and policy development.