Climate Projections

Ahmed, Kazi Farzan, Guiling Wang, John Silander, Adam M. Wilson, Jenica M. Allen, Radley Horton, and Richard Anyah. 2013. Statistical downscaling and bias correction of climate model outputs for climate change impact assessment in the U.S. northeast. Global and Planetary Change 100: 320-332.

Abstract. Statistical downscaling can be used to efficiently downscale a large number of General Circulation Model (GCM) outputs to a fine temporal and spatial scale. To facilitate regional impact assessments, this study statistically downscales (to 1/8° spatial resolution) and corrects the bias of daily maximum and minimum temperature and daily precipitation data from six GCMs and four Regional Climate Models (RCMs) for the northeast United States (US) using the Statistical Downscaling and Bias Correction (SDBC) approach. Based on these downscaled data from multiple models, five extreme indices were analyzed for the future climate to quantify future changes of climate extremes. For a subset of models and indices, results based on raw and bias corrected model outputs for the present-day climate were compared with observations, which demonstrated that bias correction is important not only for GCM outputs, but also for RCM outputs. For future climate, bias correction led to a higher level of agreements among the models in predicting the magnitude and capturing the spatial pattern of the extreme climate indices. We found that the incorporation of dynamical downscaling as an intermediate step does not lead to considerable differences in the results of statistical downscaling for the study domain.

Dai, Aiguo. 2013. Increasing drought under global warming in observations and models. Nature Climate Change 3(1): 52-58.

Abstract. Historical records of precipitation, streamflow and drought indices all show increased aridity since 1950 over many land areas. Analyses of model-simulated soil moisture, drought indices and precipitation-minus-evaporation[7] suggest increased risk of drought in the twenty-first century. There are, however, large differences in the observed and model-simulated drying patterns. Reconciling these differences is necessary before the model predictions can be trusted. Previous studies show that changes in sea surface temperatures have large influences on land precipitation and the inability of the coupled models to reproduce many observed regional precipitation changes is linked to the lack of the observed, largely natural change patterns in sea surface temperatures in coupled model simulations. Here I show that the models reproduce not only the influence of El Niño-Southern Oscillation on drought over land, but also the observed global mean aridity trend from 1923 to 2010. Regional differences in observed and model-simulated aridity changes result mainly from natural variations in tropical sea surface temperatures that are often not captured by the coupled models. The unforced natural variations vary among model runs owing to different initial conditions and thus are irreproducible. I conclude that the observed global aridity changes up to 2010 are consistent with model predictions, which suggest severe and widespread droughts in the next 30–90 years over many land areas resulting from either decreased precipitation and/or increased evaporation.

Carbon and Carbon Storage

Chen, Shutao, Yao Huang, Jianwen Zou, and Yanshu Shi. 2013. Mean residence time of global topsoil organic carbon depends on temperature, precipitation and soil nitrogen. Global and Planetary Change 100: 99-108.

Abstract. Mean residence time (MRT) of topsoil organic carbon is one critical parameter for predicting future land carbon sink dynamics. Large uncertainties remain about controls on the variability in global MRT of soil organic carbon. We estimated global MRT of topsoil (0–20 cm) organic carbon in terrestrial ecosystems and found that mean annual air temperature, annual precipitation, and topsoil nitrogen storage were responsible for the variability in MRT. An empirical climate and soil nitrogen-based (Clim&SN) model could be used to explain the temporal and spatial variability in MRT across various ecosystems. Estimated MRT was lowest in the low-latitude zones, and increased toward high-latitude zones. Global MRT of topsoil organic carbon showed a significant declining tendency between 1960 and 2008, particularly in the high-latitude zone of the northern hemisphere. The largest absolute and relative changes (0.2% per yr) in MRT of topsoil organic carbon from 1960 to 2008 occurred in high-latitude regions, consistent with large carbon stocks in, and greater degree of climate change being experienced by, these areas. Overall, global MRT anomalies (differences between MRT in each year and averaged value of MRT from 1960 to 2008) of terrestrial topsoil organic carbon were decreasing from 1960 to 2008. Global MRT anomalies decreased significantly ($P < 0.001$) with the increase of global temperature anomalies, indicating that global warming resulted in faster turnover rates of topsoil organic carbon.

Hilger, A. B., C. H. Shaw, J. M. Metsaranta, and W. A. Kurz. 2012. Estimation of snag carbon transfer rates by ecozone and lead species for forests in Canada. Ecological Applications 22:2078–2090. http://dx.doi.org/10.1890/11-2277.1

Abstract. Standing dead trees (snags) and downed woody debris contribute substantially to the carbon (C) budget of Canada's forest. Accurate parameterization of the C transfer rates (CTRs) from snags to downed woody debris is important for forest C dynamics models such as the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), but CTRs are rarely measured or reported in the literature. Therefore, forest C models generally use snag fall rates (FRs) available in the literature, as a proxy for CTRs. However, FRs are based on stem counts while CTRs refer to mass transfers. Stem mass and stem number are not linearly related, with small diameter trees representing disproportionately lower C mass transfers. Therefore this proxy, while convenient, may bias C transfer from standing dead to downed woody material. Here, we combined tree data from 10 802 sample plots and previously published species-specific individual-tree relationships between tree diameter (diameter at breast height, dbh) and fall rate to derive stand-level estimates of CTRs for the CBM-CFS3. We estimated CTRs and FRs and used the FR values to validate this approach by comparing them with standardized FR values compiled from the literature. FRs generally differed from CTRs. The overall CTR (4.78% ± 0.02% per year, mean ± SE) was significantly smaller than the overall FR (5.40% ± 0.02% per year; mean ± SE). Both the difference between FR and CTR (FR − CTR) and the CTR itself varied by ecozone, with ecozone means for CTR ranging from 3.94% per year to 10.02% per year. This variation was explained, in part, by heterogeneity in species composition, size (dbh distribution), structure, and age of the stands. The overall mean CTR estimated for the Snag_Stemwood (4.78%

per year) and the Snag_Branches (11.95% per year) pools of the CBM-CFS3 were approximately 50% and 20% higher than the current default rates used in the CBM-CFS3 of 3.2% and 10.0%, respectively. Our results demonstrate that using CTRs to estimate the annual C transfer from standing dead trees to downed woody biomass will yield more accurate estimates of C fluxes than using a FR proxy, and this accuracy could be further improved by accounting for differences in ecozone, stand component (hardwood or softwood), or lead species.

King, Anthony W, Daniel J Hayes, Deborah N Huntzinger, Tristram O West, and Wilfred M Post. 2012. North American carbon dioxide sources and sinks: magnitude, attribution, and uncertainty. Frontiers in Ecology and the Environment 10: 512–519. http://dx.doi.org/10.1890/120066

Abstract. North America is both a source and sink of atmospheric carbon dioxide (CO_2). Continental sources – such as fossil-fuel combustion in the US and deforestation in Mexico – and sinks – including most ecosystems, and particularly secondary forests – add and remove CO_2 from the atmosphere, respectively. Photosynthesis converts CO_2 into carbon as biomass, which is stored in vegetation, soils, and wood products. However, ecosystem sinks compensate for only ~35% of the continent's fossil-fuel-based CO_2 emissions; North America therefore represents a net CO_2 source. Estimating the magnitude of ecosystem sinks, even though the calculation is confounded by uncertainty as a result of individual inventory- and model-based alternatives, has improved through the use of a combined approach.

Krankina, Olga N., Mark E. Harmon, Frank Schnekenburger, and Carlos A. Sierra. 2012. Carbon balance on federal forest lands of Western Oregon and Washington: The impact of the Northwest Forest Plan. Forest Ecology and Management 286: 171-182.

Abstract. The management of federal forest lands in the Pacific Northwest (PNW) region changed in early 1990s when the Northwest Forest Plan (NWFP) was adopted with the primary goal to protect old-growth forest and associated species. A major decline in timber harvest followed, extending an earlier downward trend. The historic and projected future change in carbon (C) stores and balance on federally managed forest lands in Western Oregon (OR) and Western Washington (WA) was examined using the LANDCARB 3.0 simulation model. The projections include C stores on-site, in harvested wood products and disposal and reflect a set of contrasting visions of future forest management in the region formulated as five alternative management scenarios that extend to year 2100. A significant and long-lasting net increase in total C stores on federal forest lands relative to early 1990s level was projected for both OR and WA under all examined management scenarios except the *Industry Scenario* which envisioned a return to historic high levels of timber harvest. In comparison with the *Industry Scenario*, the low levels of timber harvest under the NWFP between 1993 and 2010 were estimated to increase total C stores by 86.0 TgC (5.1 TgC $year^{-1}$ or 2.16 MgC ha^{-1} $year^{-1}$) in OR; in WA the respective values were 45.2 TgC (2.66 TgC $year^{-1}$ or 1.33 Mg Cha^{-1} $year^{-1}$). The projected annual rate of C accumulation, reached a maximum between 2005 and 2020 approaching 4 TgC $year^{-1}$ in OR and 2.3 TgC $year^{-1}$ in WA, then gradually declined towards the end of projection period in 2100. Although not the original intent, the NWFP has led to a considerable increase in C stores on federal forest lands within the first decade of plan implementation and this trend can be expected to continue for several decades into the future if the limits on timber harvest set under the NWFP are

maintained. The primary goal of the NWFP to protect and restore old-growth forest may take several decades to achieve in WA whereas in OR the area protected from clearcut harvest may be insufficient to meet this goal before the end of projection period in 2100.

Post, Wilfred M., R Cesar Izaurralde, Tristram O West, Mark A Liebig, and Anthony W King. 2012. Management opportunities for enhancing terrestrial carbon dioxide sinks. Frontiers in Ecology and the Environment 10: 554–561. http://dx.doi.org/10.1890/120065

Abstract. The potential for mitigating increasing atmospheric carbon dioxide concentrations through the use of terrestrial biological carbon (C) sequestration is substantial. Here, we estimate the amount of C being sequestered by natural processes at global, North American, and national US scales. We present and quantify, where possible, the potential for deliberate human actions – through forestry, agriculture, and use of biomass-based fuels – to augment these natural sinks. Carbon sequestration may potentially be achieved through some of these activities but at the expense of substantial changes in land-use management. Some practices (eg reduced tillage, improved silviculture, woody bioenergy crops) are already being implemented because of their economic benefits and associated ecosystem services. Given their cumulative greenhouse-gas impacts, other strategies (eg the use of biochar and cellulosic bioenergy crops) require further evaluation to determine whether widespread implementation is warranted.

Rantakari, Miitta, Aleksi Lehtonen, Tapio Linkosalo, Mikko Tuomi, Pekka Tamminen, Juha Heikkinen, Jari Liski, Raisa Mäkipää, Hannu Ilvesniemi, Risto Sievänen. 2012. The Yasso07 soil carbon model – Testing against repeated soil carbon inventory. Forest Ecology and Management 286: 137-147.

Abstract. Forest soils store large amounts of carbon (C), and releases of C from this pool may significantly increase the CO_2 concentration in the atmosphere. Organic matter decomposition in soils has been shown to strongly depend on temperature and soil moisture and is, therefore, susceptible to the climate change. Reliable methods are needed to monitor and predict the changes in soil C stocks. In this study, we tested the Yasso07 soil C model by comparing the model predictions to repeated soil C measurements of organic layer and, furthermore, to the estimates of two other C models, namely Yasso and ROMUL. In the model simulations, we used the litter input time series derived from forest biomass estimates based on the national forest inventories. Both the repeated empirical measurements and Yasso07 simulations indicated upland forest soils to be small sinks of C in Southern Finland. The Yasso07 model was able to predict both soil C stock and C accumulation within the error limits of the measured values. Yasso07 and the earlier version, Yasso, predicted very similar soil C stocks close to the measured values, but slightly underestimated C accumulation. The annual soil C changes predicted by the Yasso07 and ROMUL models were reasonably close to each other, even though the models are based on a very different basic structure. However, the differences in the model predictions were at the highest in years with the highest precipitation, indicating that there are still uncertainties in predicting the effects of soil moisture on the soil C stock changes.

Species Range Changes

Franklin, J., Davis, F. W., Ikegami, M., Syphard, A. D., Flint, L. E., Flint, A. L. and Hannah, L. 2013. Modeling plant species distributions under future climates: how fine scale do climate projections need to be?. Global Change Biology 19(2): 473–483. doi: 10.1111/gcb.12051

Abstract. Recent studies suggest that species distribution models (SDMs) based on fine-scale climate data may provide markedly different estimates of climate-change impacts than coarse-scale models. However, these studies disagree in their conclusions of how scale influences projected species distributions. In rugged terrain, coarse-scale climate grids may not capture topographically controlled climate variation at the scale that constitutes microhabitat or refugia for some species. Although finer scale data are therefore considered to better reflect climatic conditions experienced by species, there have been few formal analyses of how modeled distributions differ with scale. We modeled distributions for 52 plant species endemic to the California Floristic Province of different life forms and range sizes under recent and future climate across a 2000-fold range of spatial scales (0.008–16 km^2). We produced unique current and future climate datasets by separately downscaling 4 km climate models to three finer resolutions based on 800, 270, and 90 m digital elevation models and deriving bioclimatic predictors from them. As climate-data resolution became coarser, SDMs predicted larger habitat area with diminishing spatial congruence between fine- and coarse-scale predictions. These trends were most pronounced at the coarsest resolutions and depended on climate scenario and species' range size. On average, SDMs projected onto 4 km climate data predicted 42% more stable habitat (the amount of spatial overlap between predicted current and future climatically suitable habitat) compared with 800 m data. We found only modest agreement between areas predicted to be stable by 90 m models generalized to 4 km grids compared with areas classified as stable based on 4 km models, suggesting that some climate refugia captured at finer scales may be missed using coarser scale data. These differences in projected locations of habitat change may have more serious implications than net habitat area when predictive maps form the basis of conservation decision making.

Mealor, Brian A., Samuel Cox, and D. Terrance Booth. 2012. Postfire Downy Brome (*Bromus tectorum*) Invasion at High Elevations in Wyoming. Invasive Plant Science and Management 5(4): 427-435.

Abstract. The invasive annual grass downy brome is the most ubiquitous weed in sagebrush systems of western North America. The center of invasion has largely been the Great Basin region, but there is an increasing abundance and distribution in the Rocky Mountain States. We evaluated postfire vegetation change using very large–scale aerial (VLSA) and near-earth imagery in an area where six different fires occurred over a 4-yr period at elevations ranging from 1,900 to over 2,700 m. The frequency of downy brome increased from 8% in 2003 to 44% in 2008 and downy brome canopy cover increased from < 1% in 2003 to 6% in 2008 across the entire study area. Principal component analyses of vegetation cover indicate a shift from plant communities characterized by high bare soil and forbs immediately postfire to communities with increasing downy brome cover with time after fire. The highest-elevation sampling area exhibited the least downy brome cover, but cover at some midelevation locations approached 100%. We postulate that the loss of ground-level shade beneath shrubs and conifers, accompanied by diminished perennial vegetative

cover, created conditions suitable for downy brome establishment and dominance. Without a cost-effective means of landscape-scale downy brome control, and with infestation levels and climate warming increasing, we predict there will be continued encroachment of downy brome at higher elevations and latitudes where disturbance creates suitable conditions.

Forest Vegetation

Boucher-Lalonde, Véronique, Antoine Morin, and David J. Currie. 2012. How are tree species distributed in climatic space? A simple and general pattern. Global Ecology and Biogeography 21(12): 1157–1166.

Aim Although many factors undoubtedly affect species geographic distributions, can a single, simple model nonetheless capture most of the spatial variation in the probability of presence/absence in a large set of species? For 482 North American tree species that occur east of the Rocky Mountains, we investigated the shape(s) of the relationship between the probability of occupancy of a given location and macroclimate, and its consistency among species and regions.

Location North America.

Methods Using Little's tree range maps, we tested four hypothetical shapes of response relating occupancy to climate: (1) high occupancy of all suitable climates; (2) threshold response (i.e. unsuitable climates exclude species, but within the thresholds, species presence is independent of climate); (3) occupancy is a bivariate normal function of annual temperature and precipitation; and (4) asymmetric limitation (i.e. abiotic factors set abrupt range limits in stressful climates only). Finally, we compared observed climatic niches with the occupancy of similar climates on off-shore islands as well as west of the Rockies.

Results (a) Species' distributions in climatic space do not have strong thresholds, nor are they systematically skewed towards less stressful climates. (b) Occupancy can generally be described by a bivariate normal function of temperature and precipitation, with little or no interaction between the two variables. This model, averaged over all species, accounts for 82% of the spatial variation in the probability of occupancy of a given area. (c) Occupied geographic ranges are typically ringed by unoccupied, but climatically suitable areas. (d) Observed climatic niche positions are largely conserved between regions.

Main conclusions We conclude that, despite the complexities of species histories and biologies, to a first approximation most of the variation in their geographic distributions relates to climate, in similar ways for nearly all species.

Carnwath, Gunnar C., David W. Peterson and Cara R. Nelson. 2012. Effect of crown class and habitat type on climate–growth relationships of ponderosa pine and Douglas-fir. Forest Ecology and Management 285: 44-52.

Abstract. There is increasing interest in actively managing forests to increase their resilience to climate-related changes. Although forest managers rely heavily on the use of silvicultural treatments that manipulate stand structure and stand dynamics to modify responses to climate change, few studies have directly assessed the effects of stand structure or canopy position on climate–growth relationships – or examined

how this relationship may vary among species or across environmental gradients. In this study, we analyzed variability in tree-ring series from 15 low-elevation stands in northeastern Washington (USA) using time series analysis and linear mixed effects models. Our objective was to assess the relative influences of species (*Pinus ponderosa* vs. *Pseudotsuga menziesii*), crown class (dominant vs. intermediate), and habitat type (Xeric vs. Dry-Mesic) on the climate responses of mature trees in unmanaged forests. We found that climate–growth relationships varied significantly between canopy classes and across habitat types but that these effects were highly species-specific. For *P. menziesii*, growth responses to temperature and precipitation did not vary between canopy classes. For *P. ponderosa*, however, regression coefficients for the relationship between temperature and radial growth were nearly twice as large for dominant trees compared to intermediate trees, and 84% of dominant trees were significantly influenced by precipitation, compared to only 62% of intermediate trees. In contrast, habitat-type did not significantly affect the climate responses of *P. ponderosa*, but did affect responses of *P. menziesii.* For example, for *P. menziesii* only 51% of trees in Dry-Mesic sites, were significantly affected by drought (PDSI), compared to 93% in Xeric sites. A better understanding of the relationship between climate sensitivity, species-specific hydraulic strategies, and stand dynamics is crucial for accurately predicting tree responses to climate change and designing forest treatments that will effectively reduce the climatic vulnerability of key forest species and habitats. Results may assist managers with understanding how altering stand dynamics will differentially affect climate-responses of individual species.

Redmond, Miranda D., Frank Forcella, and Nichole N. Barger. 2012. Declines in pinyon pine cone production associated with regional warming. Ecosphere 3:art120. http://dx.doi.org/10.1890/ES12-00306.1

Abstract. Global climate change is expected to produce large shifts in vegetation distribution and has already increased tree mortality, altering forest structure. However, long-term shifts will be partly dependent on the ability of species to reproduce under a novel climate. Few studies have examined the impact of climate change on the reproductive output of long-lived 'masting' species, or species characterized by episodic reproductive events. Here, we show that seed cone production among pinyon pine (*Pinus edulis*), a masting species, declined by 40% from the 1974 decade (1969–1978) to the 2008 decade (2003–2012) in revisited stands throughout New Mexico and northwestern Oklahoma. Seed cone production was highly correlated with late summer temperatures at the time of cone initiation. Further, declines in seed cone production were greatest among populations that experienced the greatest increases in growing season temperatures, which were the populations located at the cooler, upper elevations. As growing season temperatures are predicted to increase across this region over the next century, these findings suggest seed cone production may be an increasingly important bottleneck for future pinyon pine regeneration, especially in areas with greater increases in temperature. Declines in seed cone production may not only affect pinyon pine population dynamics but also the various wildlife species that rely on pinyon pine seeds. Because pinyon pine has similar reproductive strategies as other semi-arid pine species, increasing temperature may negatively influence reproductive output of other conifers. Further investigation into the full geographic and taxonomic extent of these seed declines is warranted.

Rollinson, Christine R., Margot W. Kaye, and Laura P. Leites. 2012. Community assembly responses to warming and increased precipitation in an early successional forest. Ecosphere 3:art122. http://dx.doi.org/10.1890/ES12-00321.1

Abstract. Experimental climate manipulations provide the opportunity to link predicted changes in climate to the process of community assembly. We studied plant community assembly of a recently harvested forest exposed to three years of experimental 2°C warming and 20% increased precipitation. By the end of the experiment, trees were the only functional group that shifted composition in response to warming and precipitation treatments ($p = 0.03$), while the composition of the grass, forbs, and shrub/small tree/vine functional groups were unresponsive. Individual species within groups were associated with specific treatments, but did not result in a predictable community composition shift. Temporal dynamics of functional group cover were more sensitive to treatment effects than single, static measures of plant community responses such as biomass. Both static and dynamic plant analyses revealed interactive effects of warming and increased precipitation on cover and biomass of grass and all plants together (grass cover $p < 0.01$, grass biomass $p = 0.02$, total cover $p < 0.01$, total biomass $p = 0.05$). Short forb cover was negatively affected by increased precipitation throughout our experiment ($p = 0.03$). Grass, tree, and shrub/small tree/vine functional groups showed independent year effects on cover that can be attributed to successional development of the forest community (all $p \leq 0.01$). Random forest modeling indicated that cover of other plant functional groups and static plot-level variables such as plot location and components of soil texture were often the most important predictors of cover for a given functional group, while temperature and moisture availability measures were the least important. Importance of predictors of functional group cover varied greatly among random forest models from different treatments, suggesting that diverse environmental factors constrain functional group cover and may provide resilience of community assembly to climate change.

Silva, Lucas C. R. and Madhur Anand. 2013. Probing for the influence of atmospheric CO_2 and climate change on forest ecosystems across biomes. Global Ecology and Biogeography 22(1): 83-92.

Aim. Rising atmospheric CO_2 and climate warming have induced changes in tree growth and intrinsic water-use efficiency (iWUE) world-wide, but the long-term impact of such changes on terrestrial productivity remains unknown. Based on a synthesis of the literature, here we investigate the net impact of recent atmospheric changes across forest biomes.

Location. A range of sites covering major forest biomes.

Methods. We use dendrochronological and isotopic records to provide an integrated analysis of changes in growth and iWUE, evaluating the impacts of atmospheric changes in tree growth. In our analysis, positive relationships between changes in growth and iWUE reflect CO_2 stimulation, while neutral effects yield inflections in growth curves (plotted against iWUE), and negative relationships indicate the prevalence of stressors. To estimate net effects (since 1960) and compare responses across biomes, we use a response contrast (RC) index, based on the ratio between cumulative changes in growth and iWUE.

Results. In 37 recently published case studies changes in iWUE were consistently positive, increasing by between 10 and 60%, but shifts in growth varied widely within and among forest biomes. Positive RC values were observed in high latitudes

(> 40°N), while progressively lower (always negative) responses were observed toward lower latitudes. Growth rates declined between 15 and 55% in tropical forests. In subtropical sites growth declined by between 7 and 10%, while mixed responses occurred in other regions.

Main conclusions. Over the past 50 years, tree growth decline has prevailed despite increasing atmospheric CO_2. The impact of atmospheric changes on forest productivity is latitude dependent ($R^2 = 0.9$, $P < 0.05$), but our results suggest that, globally, CO_2 stimulation of mature trees will not counteract emissions. In most surveyed case studies warming-induced stress was evoked to explain growth decline, but other factors, such as nutrient limitation, could have overridden the potential benefits of rising CO_2 levels.

Vose, James M., David L. Peterson, Toral Patel-Weynand, eds. 2013. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. Gen. Tech. Rep. PNW-GTR-870. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. 265 p. Available at http://www.fs.fed.us/pnw/publications/gtrs.shtml.

Abstract. This report is a scientific assessment of the current condition and likely future condition of forest resources in the United States relative to climatic variability and change. It serves as the U.S. Forest Service forest sector technical report for the National Climate Assessment and includes descriptions of key regional issues and examples of a risk-based framework for assessing climate-change effects.

By the end of the 21st century, forest ecosystems in the United States will differ from those of today as a result of changing climate. Although increases in temperature, changes in precipitation, higher atmospheric concentrations of carbon dioxide (CO_2), and higher nitrogen (N) deposition may change ecosystem structure and function, the most rapidly visible and most significant short-term effects on forest ecosystems will be caused by altered disturbance regimes. For example, wildfires, insect infestations, pulses of erosion and flooding, and drought-induced tree mortality are all expected to increase during the 21st century. These direct and indirect climate-change effects are likely to cause losses of ecosystem services in some areas, but may also improve and expand ecosystem services in others. Some areas may be particularly vulnerable because current infrastructure and resource production are based on past climate and steady-state conditions. The ability of communities with resource-based economies to adapt to climate change is linked to their direct exposure to these changes, as well as to the social and institutional structures present in each environment. Human communities that have diverse economies and are resilient to change today will also be prepared for future climatic stresses.

Significant progress has been made in developing scientific principles and tools for adapting to climate change through science-management partnerships focused on education, assessment of vulnerability of natural resources, and development of adaptation strategies and tactics. In addition, climate change has motivated increased use of bioenergy and carbon (C) sequestration policy options as mitigation strategies, emphasizing the effects of climate change-human interactions on forests, as well as the role of forests in mitigating climate change. Forest growth and afforestation in the United States currently account for a net gain in C storage and offset approximately 13 percent of the Nation's fossil fuel CO_2 production. Climate change mitigation through forest C management focuses on (1) land use change to increase forest area (afforestation) and avoid deforestation, (2) C management in

existing forests, and (3) use of wood as biomass energy, in place of fossil fuel or in wood products for C storage and in place of other building materials. Although climate change is an important issue for management and policy, the interaction of changes in biophysical environments (e.g., climate, disturbance, and invasive species) and human responses to those changes (management and policy) will ultimately determine outcomes for ecosystem services and people.

Although uncertainty exists about the magnitude and timing of climate-change effects on forest ecosystems, sufficient scientific information is available to begin taking action now. Building on practices compatible with adapting to climate change provides a good starting point for land managers who may want to begin the adaptation process. Establishing a foundation for managing forest ecosystems in the context of climate change as soon as possible will ensure that a broad range of options will be available for managing forest resources sustainably.

Rangeland Vegetation

Bykova, Olga and Rowan F. Sage. 2012. Winter cold tolerance and the geographic range separation of *Bromus tectorum* and *Bromus rubens,* two severe invasive species in North America. Global Change Biology 18(12): 3654-3663.

Abstract. The invasive grasses *Bromus rubens* and *Bromus tectorum* are responsible for widespread damage to semiarid biomes of western North America. *Bromus. tectorum* dominates higher and more northern landscapes than its sister species *B. rubens*, which is a severe invader in the Mojave desert region of the American Southwest. To assess climate thresholds controlling their distinct geographic ranges, we evaluated the winter cold tolerance of *B. tectorum* and *B. rubens*. Freezing tolerance thresholds were determined using electrolyte leakage and whole-plant mortality. The responses of the two species to winter cold and artificial freezing treatments were similar in 2007–2008 and 2009–2010. When grown at minimum temperatures of 10 °C, plants of both species had cold tolerance thresholds near −10 °C, while plants acclimated to a daily minimum of −10 to −30 °C survived temperatures down to −31 °C. In the winter of 2010–2011, a sudden severe cold event on December 9, 2010 killed all *B. rubens* populations, while *B. tectorum* was not harmed; all tested plants were 7–8 weeks old. Controlled acclimation experiments demonstrated that 8-week-old plants of *B. rubens* had a slower acclimation rate to subzero temperatures than *B. tectorum* and could not survive a rapid temperature drop from 1 to −14 °C. Four-month-old *B. rubens* populations were as cold tolerant as *B. tectorum*. Our results show that severe and sudden freeze events in late autumn can kill young plants of *B. rubens* but not *B. tectorum*. Such events could exclude *B. rubens* from the relatively cold, Intermountain steppe biome of western North America where *B. tectorum* predominates.

Craine, Joseph M., Troy W. Ocheltree, Jesse B. Nippert, E. Gene Towne, Adam M. Skibbe, Steven W. Kembel and Joseph E. Fargione. 2013. Global diversity of drought tolerance and grassland climate-change resilience. Nature Climate Change 3(1): 63-67.

Abstract. Drought reduces plant productivity, induces widespread plant mortality and limits the geographic distribution of plant species. As climates warm and precipitation patterns shift in the future, understanding the distribution of the diversity of plant drought tolerance is central to predicting future ecosystem function and resilience to climate change. These questions are especially pressing for the world's 11,000 grass species, which dominate a large fraction of the terrestrial biosphere[14], yet are poorly characterized with respect to responses to drought. Here, we show that physiological drought tolerance, which varied tenfold among 426 grass species, is well distributed both climatically and phylogenetically, suggesting most native grasslands are likely to contain a high diversity of drought tolerance. Consequently, local species may help maintain ecosystem functioning in response to changing drought regimes without requiring long-distance migrations of grass species. Furthermore, physiologically drought-tolerant species had higher rates of water and carbon dioxide exchange than intolerant species, indicating that severe droughts may generate legacies for ecosystem functioning. In all, our findings suggest that diverse grasslands throughout the globe have the potential to be resilient to drought in the face of climate change through the local expansion of drought-tolerant species.

Fish and Wildlife

Auer, S. K. and Martin, T. E. 2013. Climate change has indirect effects on resource use and overlap among coexisting bird species with negative consequences for their reproductive success. Global Change Biology 19(2): 411–419. doi: 10.1111/gcb.12062

Abstract. Climate change can modify ecological interactions, but whether it can have cascading effects throughout ecological networks of multiple interacting species remains poorly studied. Climate-driven alterations in the intensity of plant–herbivore interactions may have particularly profound effects on the larger community because plants provide habitat for a wide diversity of organisms. Here we show that changes in vegetation over the last 21 years, due to climate effects on plant–herbivore interactions, have consequences for songbird nest site overlap and breeding success. Browsing-induced reductions in the availability of preferred nesting sites for two of three ground nesting songbirds led to increasing overlap in nest site characteristics among all three bird species with increasingly negative consequences for reproductive success over the long term. These results demonstrate that changes in the vegetation community from effects of climate change on plant–herbivore interactions can cause subtle shifts in ecological interactions that have critical demographic ramifications for other species in the larger community.

Buisson, L., Grenouillet, G., Villéger, S., Canal, J. and Laffaille, P. 2013. Toward a loss of functional diversity in stream fish assemblages under climate change. Global Change Biology 19(2): 387–400. doi: 10.1111/gcb.12056

Abstract. The assessment of climate change impacts on biodiversity has so far been biased toward the taxonomic identification of the species likely either to benefit from climate modifications or to experience overall declines. There have still been few studies intended to correlate the characteristics of species to their sensitivity to climate change, even though it is now recognized that functional trait-based approaches are promising tools for addressing challenges related to global changes. In this study, two functional indices (originality and uniqueness) were first measured for 35 fish species occurring in French streams. They were then combined to projections of range shifts in response to climate change derived from species distribution models. We set out to investigate: (1) the relationship between the degrees of originality and uniqueness of fish species, and their projected response to future climate change; and (2) the consequences of individual responses of species for the functional diversity of fish assemblages. After accounting for phylogenetic relatedness among species, we have demonstrated that the two indices used measure two complementary facets of the position of fish species in a functional space. We have also rejected the hypothesis that the most original and/or less redundant species would necessarily experience the greatest declines in habitat suitability as a result of climate change. However, individual species range shifts could lead simultaneously both to a severe decline in the functional diversity of fish assemblages, and to an increase in the functional similarity among assemblages, supporting the hypothesis that disturbance favors communities with combination of common traits and biotic homogenization as well. Our findings therefore emphasize the importance of going beyond the simple taxonomic description of diversity to provide a better assessment of the likely future effects of environmental changes on biodiversity, thus helping to design more effective conservation and management measures.

Dzialak, Matthew R., Stephen L. Webb, Seth M. Harju, Chad V. Olson, Jeffrey B. Winstead, and Larry D. Hayden-Wing. 2013. Greater Sage-Grouse and Severe Winter Conditions: Identifying Habitat for Conservation. Rangeland Ecology and Management 66(1): 10-18.

Abstract. Developing sustainable rangeland management strategies requires solution-driven research that addresses ecological issues within the context of regionally important socioeconomic concerns. A key sustainability issue in many regions of the world is conserving habitat that buffers animal populations from climatic variability, including seasonal deviation from long-term precipitation or temperature averages, and that can establish an ecological bottleneck by which the landscape-level availability of critical resources becomes limited. We integrated methods to collect landscape-level animal occurrence data during severe winter conditions with estimation and validation of a resource selection function, with the larger goal of developing spatially explicit guidance for rangeland habitat conservation. The investigation involved greater sage-grouse (*Centrocercus urophasianus*) that occupy a landscape that is undergoing human modification for development of energy resources. We refined spatial predictions by exploring how reductions in the availability of sagebrush (as a consequence of increasing snow depth) may affect patterns of predicted occurrence. Occurrence of sage-grouse reflected landscape-level selection for big sagebrush, taller shrubs, and favorable thermal conditions and avoidance of bare ground and anthropogenic features.

Refinement of spatial predictions showed that important severe winter habitat was distributed patchily and was constrained in spatial extent (7–18% of the landscape). The mapping tools we developed offer spatially explicit guidance for planning human activity in ways that are compatible with sustaining habitat that functions disproportionately in population persistence relative to its spatial extent or frequency of use. Increasingly, place-based, quantitative investigations that aim to develop solutions to landscape sustainability issues will be needed to keep pace with human-modification of rangeland and uncertainty associated with global climate change and its effects on animal populations.

Hydrology

Wu, Chaoyang, Jing M. Chen, Ankur R. Desai, Peter M. Lafleur, and Shashi B. Verma. 2013. Positive impacts of precipitation intensity on monthly CO_2 fluxes in North America. Global and Planetary Change 100: 204-214.

Abstract. Precipitation is one of the most important climate factors that can affect the gross ecosystem production (GEP) of terrestrial ecosystems. Positive impacts of precipitation on annual GEP have been reported for vegetated areas worldwide. However, little is known about the influence of precipitation intensity on GEP, especially at the monthly to seasonal temporal scale. Here we show that monthly GEP is insensitive to the sum of monthly total precipitation (P_s, mm), but positively correlated to precipitation intensity (P_a, mm), defined as the average precipitation per event from half-hourly measurements over a month. Different plant functional types (PFTs) exhibit substantial differences in the sensitivity of monthly GEP to P_a. PFTs of water-limited regions responded more intensely than those in mesic environments, as demonstrated by a negative correlation between the slope of the GEP-P_a regression line and average P_a. Furthermore, this slope increases with latitude, indicating higher sensitivity of GEP to P_a for boreal ecosystems than for temperate regions. Therefore, we anticipate increased intensity of storms, as projected by some climate models, may impart a previously overlooked positive impact on precipitation intensity on GEP.

Sea Level

Schaeffer, Michiel, William Hare, Stefan Rahmstorf and Martin Vermeer. 2012. Long-term sea-level rise implied by 1.5°C and 2°C warming levels. Nature Climate Change 2(12): 867-870.

Abstract. Sea-level rise (SLR) is a critical and uncertain climate change risk, involving timescales of centuries. Here we use a semi-empirical model, calibrated with sea-level data of the past millennium, to estimate the SLR implications of holding warming below 2 °C or 1.5 °C above pre-industrial temperature, as mentioned in the Cancún Agreements. Limiting warming to these levels with a probability larger than 50% produces 75–80 cm SLR above the year 2000 by 2100. This is 25 cm below a scenario with unmitigated emissions, but 15 cm above a hypothetical scenario reducing global emissions to zero by 2016. The long-term SLR implications of the two warming goals diverge substantially on a multi-century

timescale owing to inertia in the climate system and the differences in rates of SLR by 2100 between the scenarios. By 2300 a 1.5 °C scenario could peak sea level at a median estimate of 1.5 m above 2000. The 50% probability scenario for 2 °C warming would see sea level reaching 2.7 m above 2000 and still rising at about double the present-day rate. Halting SLR within a few centuries is likely to be achieved only with the large-scale deployment of CO_2 removal efforts, for example, combining large-scale bioenergy systems with carbon capture and storage.

Zecca, Antonio and Luca Chiari. 2012. Lower bounds to future sea-level rise. Global and Planetary Change 98-99: 1-5.

Abstract. Sea-level rise is among the most important changes expected as a consequence of anthropogenic global warming. Climate model-based projections made until the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) yield a 21st century rise spanning nearly 20–60 cm. However, it is known that current climate models are likely to underestimate sea-level change in response to rapid climatic variations. Recent alternative semi-empirical approaches predict a much higher sea-level rise than the IPCC AR4 projections. Nevertheless, the underway depletion of conventional fossil fuels might, at least in principle, constrain future fossil CO_2 emissions and, in turn, affect also the extent of sea-level rise. Here we project 2000–2200 sea-level rise with a semi-empirical method coupled to a simple climate model that is run under a range of fossil-fuel exhaustion scenarios. We find that, in spite of fossil-fuel depletion, sea level is predicted to rise by at least ~ 80 cm at the end of this century and is expected to continue rising for at least the next two hundred years. The present results support the need for prompt and substantial emission cuts in order to slow down future sea-level rise and implement adaptation measures.

Adaptation

Beier, Paul. 2012. Conceptualizing and Designing Corridors for Climate Change. Ecological Restoration 30(4): 312-319. doi 10.3368/er.30.4.312

Abstract. In the rush to embrace corridors as an adaptation strategy, some ecologists have framed the strategy as using complex models to design corridors extending hundreds of kilometers from low-elevation, low-latitude sites to distant high-elevation, poleward sites along paths that capture the shifting climate envelopes of individual species. This conceptualization of corridors differs from traditional corridors designed to support gene flow and recolonization. In contrast, I argue that both short-distance and long-distance shifts to future climate space can be achieved by a combination of short movements within large, topographically and climatically diverse natural landscape blocks and short, coarse filter corridors between those blocks. These coarse-filter corridors can be designed in 3 non-mutually-exclusive ways. First, rivers areas provide natural conduits for movement of plants and animals and are therefore priorities for conservation and restoration as climate corridors. Second, linkages that provide continuity and interspersion of land facets (units defined by topographic or soil variables) should support movement under any future climate regime. This approach is best suited to link large topographically diverse blocks separated by distances < 30 km. The third approach, climate gradient corridors, is appropriate in landscapes where natural landscape

blocks have low within-block topographic diversity (such as where blocks are small), especially if the blocks are dissimilar. The coarse filter approaches described here are reasonable and well-grounded in fundamental concepts of ecology, but conservation and restoration decisions should also be based on empirical evidence of how well coarse filter corridors protect demographic and genetic flows for today's focal species.

Cross, Molly S., Patrick D. McCarthy and Gregg Garfin. 2013. Accelerating Adaptation of Natural Resource Management to Address Climate Change. Conservation Biology 27(1): 4-13.

Abstract. Natural resource managers are seeking tools to help them address current and future effects of climate change. We present a model for collaborative planning aimed at identifying ways to adapt management actions to address the effects of climate change in landscapes that cross public and private jurisdictional boundaries. The Southwest Climate Change Initiative (SWCCI) piloted the Adaptation for Conservation Targets (ACT) planning approach at workshops in 4 southwestern U.S. landscapes. This planning approach successfully increased participants' self-reported capacity to address climate change by providing them with a better understanding of potential effects and guiding the identification of solutions. The workshops fostered cross-jurisdictional and multidisciplinary dialogue on climate change through active participation of scientists and managers in assessing climate change effects, discussing the implications of those effects for determining management goals and activities, and cultivating opportunities for regional coordination on adaptation of management plans. Facilitated application of the ACT framework advanced group discussions beyond assessing effects to devising options to mitigate the effects of climate change on specific species, ecological functions, and ecosystems. Participants addressed uncertainty about future conditions by considering more than one climate-change scenario. They outlined opportunities and identified next steps for implementing several actions, and local partnerships have begun implementing actions and conducting additional planning. Continued investment in adaptation of management plans and actions to address the effects of climate change in the southwestern United States and extension of the approaches used in this project to additional landscapes are needed if biological diversity and ecosystem services are to be maintained in a rapidly changing world.

Lunt, Ian D., Margaret Byrne, Jessica J. Hellmann, Nicola J. Mitchell, Stephen T. Garnett, Matt W. Hayward, Tara G. Martin, Eve McDonald-Maddden, Stephen E. Williams, and Kerstin K. Zander. 2013. Using assisted colonisation to conserve biodiversity and restore ecosystem function under climate change. Biological Conservation 157: 172-177.

Abstract. Assisted colonisation has received considerable attention recently, and the risks and benefits of introducing taxa to sites beyond their historical range have been vigorously debated. The debate has primarily focused on using assisted colonization to enhance the persistence of taxa that would otherwise be stranded in unsuitable habitat as a consequence of anthropogenic climate change and habitat fragmentation. However, a complementary motivation for assisted colonisation could be to relocate taxa to restore declining ecosystem processes that support biodiversity in recipient sites. We compare the benefits and risks of species introductions motivated by either goal, which we respectively term 'push' versus 'pull' strategies for introductions to preserve single species or for restoration of

ecological processes. We highlight that, by focusing on push and neglecting pull options, ecologists have greatly under-estimated potential benefits and risks that may result from assisted colonisation. Assisted colonisation may receive higher priority in climate change adaptation strategies if relocated taxa perform valuable ecological functions (pull) rather than have little collateral benefit (push). Potential roles include enhancing resistance to invasion by undesired species, supporting co-dependent species, performing keystone functions, providing temporally critical resources, replacing taxa of low ecological redundancy, and avoiding time lags in the provisioning of desired functions.

Marshall, Nadine A. and Alex Smajgl. 2013. Understanding Variability in Adaptive Capacity on Rangelands. Rangeland Ecology and Management 66(1): 88-94.

Abstract. The art and science of developing effective policies and practices to enhance sustainability and adapt to new climate conditions on rangelands and savannas are typically founded on addressing the "average" or "typical" resource user. However, this assumption is flawed since it does not appreciate the extent of diversity among resource users; it risks that strategies will be irrelevant for many people and ignored, and that the grazing resource itself will remain unprotected. Understanding social heterogeneity is vital for effective natural resource management. Our aim was to understand the extent to which graziers in the northern Australian rangelands varied in their capacity to adapt to climate variability and recommended practices. Adaptive capacity was assessed according to four dimensions: 1) the perception of risk, 2) skills in planning, learning and reorganising, 3) financial and emotional flexibility, and 4) interest in adapting. We conducted 100 face-to-face interviews with graziers in their homes obtaining a 97% response rate. Of the 16 possible combinations that the four dimensions represent, we observed that all combinations were present in the Burdekin. Any single initiative to address grazing land management practices in the region is unlikely to address the needs of all graziers. Rather, policies could be tailored to type-specific needs based on adaptive capacity. Efforts to shift graziers from very low, low, or moderate levels of adaptive capacity are urgently needed. We suggest some strategies.

Munroe, Robert, Dilys Roe, Nathalie Doswald, Tom Spencer, Iris Möller, Bhaskar Vira, Hannah Reid, Andreas Kontoleon, Alessandra Giuliani, Ivan Castelli, and Jen Stephens. 2012. Review of the evidence base for ecosystem-based approaches for adaptation to climate change. Environmental Evidence 2012 1:13.

Abstract. Ecosystem-based approaches for adaptation (EbA) integrate the use of biodiversity and ecosystem services into an overall strategy for helping people adapt to climate change. To date, insight into these approaches has often been based on reports from isolated anecdotal case studies. Although these are informative, and provide evidence that people are using ecosystems to adapt, they provide rather limited insight in terms of measuring and evaluating the effectiveness of EbA, especially when compared with technical or structural adaptation interventions. The body of scientific evidence indicating how effective such approaches are is lacking in some aspects. Where evidence does exist it is often dispersed across a range of related fields, such as natural resource management, disaster risk reduction and agroecology. To date, there has been little attempt to systematically assemble and analyse this evidence. Therefore, the current state of evidence regarding the merits or otherwise of EbA is unknown and it has not been possible to identify prevailing

knowledge gaps to inform research and analysis, which will enable policymakers to compare EbA with other adaptation options.

Oliver, Tom H., Richard J. Smithers, Sallie Bailey, Clive A. Walmsley, and Kevin Watts. 2012. A decision framework for considering climate change adaptation in biodiversity conservation planning. Journal of Applied Ecology 49(6): 1247-1255.

Abstract. General principles of climate change adaptation for biodiversity have been formulated, but do not help prioritize actions. This is inhibiting their integration into conservation planning.

We address this need with a decision framework that identifies and prioritizes actions to increase the adaptive capacity of species. The framework classifies species according to their current distribution and projected future climate space, as a basis for selecting appropriate decision trees.

Decisions rely primarily on expert opinion, with additional information from quantitative models, where data are available. The framework considers in-situ management, followed by interventions at the landscape scale and finally translocation or ex-situ conservation.

Synthesis and applications: From eight case studies, the key interventions identified for integrating climate change adaptation into conservation planning were local management and expansion of sites. We anticipate that, in combination with consideration of socio-economic and local factors, the decision framework will be a useful tool for conservation and natural resource managers to integrate adaptation measures into conservation plans.

Temperli, Christian, Harald Bugmann, and Ché Elkin. 2012. Adaptive management for competing forest goods and services under climate change. Ecological Applications 22:2065–2077. http://dx.doi.org/10.1890/12-0210.1

Abstract. Developing adaptive forest management strategies is essential to maintain the provisioning of forest goods and services (FGS) under future climate change. We assessed how climate change and forest management affect forest development and FGS for a diverse case-study landscape in Central Europe. Using a process-based forest model (LandClim) we simulated forest dynamics and FGS under a range of climate change and management scenarios in the Black Forest, Germany, which is shaped by various management practices. We focused on the interdependencies between timber production and forest diversity, the most valued FGS in this region.

We found that the conversion to more drought-adapted forest types is required to prevent climate change-induced forest dieback and that this conversion must be the target of any adaptive management, especially in areas where monocultures of drought-sensitive Norway spruce (*Picea abies*) were promoted in the past. Forest conversion takes up to 120 years, however, with past and future adaptive management being the key drivers of timber and forest diversity provision. The conversion of drought-sensitive conifer monocultures maintains timber production in the short term and enhances a range of forest diversity indices. Using uneven-aged forest management that targets a drought-adapted, diverse, and resilient species mixture, high species diversity can be combined with timber production in the long term. Yet, the promotion of mature-stand attributes requires management

restrictions. Selecting future adaptive management options thus implies the consideration of trade-offs between forest resource use and environmental objectives, but also the exploitation of synergies between FGS that occur during forest conversion. Lastly, the large impact of past management practices on the spatial heterogeneity of forest dynamics underpins the need to assess FGS provisioning at the landscape scale.

Mitigation

Booker, Kayje, Lynn Huntsinger, James W. Bartolome, Nathan F. Sayre, and William Stewart. 2013. What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States? Global Environmental Change 23(1): 240-251.

Abstract. Scientific interest in carbon sequestration on rangelands is largely driven by their extent, while the interest of ranchers in the United States centers on opportunities to enhance revenue streams. Rangelands cover approximately 30% of the earth's ice-free land surface and hold an equivalent amount of the world's terrestrial carbon. Rangelands are grasslands, shrublands, and savannas and cover 312 million hectares in the United States. On the arid and semi-arid sites typical of rangelands annual fluxes are small and unpredictable over time and space, varying primarily with precipitation, but also with soils and vegetation. There is broad scientific consensus that non-equilibrium ecological models better explain the dynamics of such rangelands than equilibrium models, yet current and proposed carbon sequestration policies and associated grazing management recommendations in the United States often do not incorporate this developing scientific understanding of rangeland dynamics. Carbon uptake on arid and semi-arid rangelands is most often controlled by abiotic factors not easily changed by management of grazing or vegetation. Additionality may be impossible to achieve consistently through management on rangelands near the more xeric end of a rangeland climatic gradient. This point is illustrated by a preliminary examination of efforts to develop voluntary cap and trade markets for carbon credits in the United States, and options including payment for ecosystem services or avoided conversion, and carbon taxation. A preliminary analysis focusing on cap and trade and payment for avoided conversion or ecosystem services illustrates the misalignment between policies targeting vegetation management for enhanced carbon uptake and non-equilibrium carbon dynamics on arid United States rangelands. It is possible that current proposed carbon policy as exemplified by carbon credit exchange or offsets will result in a net increase in emissions, as well as investment in failed management. Rather than focusing on annual fluxes, policy and management initiatives should seek long-term protection of rangelands and rangeland soils to conserve carbon, and a broader range of environmental and social benefits.

Dilling, Lisa and Elisabeth Failey. 2013. Managing carbon in a multiple use world: The implications of land-use decision context for carbon management. Global Environmental Change 23(1): 291-300.

Abstract. Human land use contributes significantly to the growth of greenhouse gases in the atmosphere. Changes in land management practices have been proposed as a critical and cost-effective mechanism for reducing greenhouse gas

emissions and promoting the storage of additional carbon in vegetation and soils. However many discussions of the potential for land use to mitigate climate change only take into account biophysical factors such as vegetation and land cover and neglect how the agency of land owners themselves affects whether additional carbon storage can be achieved. Unlike many potential REDD opportunities in developing countries, land management in the U.S. to enhance carbon sequestration would occur against a backdrop of clearly defined, legally enforceable land ownership. In addition, more than a third of the land surface in the U.S. is managed by federal agencies who operate under legal guidelines for multiple use and is subject to demands from multiple constituencies. We set out to investigate how the goal of enhancing carbon sequestration through land use is perceived or implemented in one region of the U.S., and how this goal might intersect the existing drivers and incentives for public and private land use decision making. We conducted a case study through interviews of the major categories of landowners in the state of Colorado, which represents a mixture of public and privately held lands. By analyzing trends in interview responses across categories, we found that managing for carbon is currently a fairly low priority and we identify several barriers to more widespread consideration of carbon as a management priority including competing objectives, limited resources, lack of information, negative perceptions of offsetting and lack of a sufficient policy signal. We suggest four avenues for enhancing the potential for carbon to be managed through land use including clarifying mandates for public lands, providing compelling incentives for private landowners, improving understanding of the co-benefits and tradeoffs of managing for carbon, and creating more usable science to support decision making.