Influences of Climate Change on Water Availability in Complex Terrain: Understanding Earth Processes and their Relation to Social Action

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by

P. Zion Klos

Major Professor: Timothy Link, Ph.D.

Committee Members: Jo Ellen Force, Ph.D., Robert Heinse, Ph.D., Mark Seyfried, Ph.D.

Department Administrator: Robert Mahler, Ph.D.

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Authorization to Submit Dissertation

This dissertation of P. Zion Klos, submitted for the degree of Doctor of Philosophy with a Major in Environmental Sciences and titled "Influences of Climate Change on Water Availability in Complex Terrain: Understanding Earth Processes and their Relation to Social Action," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ____________________ Date:_____________
Timothy Link, Ph.D.

Committee Members: ____________________ Date:_____________
Jo Ellen Force, Ph.D.

____________________ Date:_____________
Robert Heinse, Ph.D.

____________________ Date:_____________
Mark Seyfried, Ph.D.

Department Administrator: ____________________ Date:_____________
Robert Mahler, Ph.D.

Abstract

Climate change and its hydrologic influences are well documented at the global scale, but local and regional changes are not as well understood. Chapter 2 describes an interdisciplinary framework that couples end users' data needs with observed, biophysical changes. An online survey of natural resource professionals in Idaho was conducted to assess the perceived impacts from climate change and determine the biophysical data needed to measure those impacts. Guided by the survey results, 15 biophysical indicator datasets were summarized. Quantitative changes in indicators were determined using time series analysis from 1975 to 2010. Indicators displayed trends of varying likelihood over the analysis period. Chapter 3 moves beyond observations, and models the future extent of the rain-snow transition zone across the complex terrain of the western United States by the mid-21st century. These projections indicate a 30 percent decrease in areal extent of winter wet-day temperatures conducive to snowfall over the western United States. Chapter 4 explores the usefulness of these and other types of climate change science for federal resource managers, focusing on the efficacy of potential adaptation strategies and barriers limiting the use of climate change science in adaptation efforts. We interacted with 77 U.S. Forest Service and Bureau of Land Management personnel through surveys, semi-structured interviews, and four collaborative workshops at locations across Idaho and Montana. We used a mixed-methods approach to evaluate managers' perceptions about adapting to and mitigating for climate change. Although resource managers incorporate general language about climate change in landscape-level planning documents, they are currently not planning on-the-ground adaptation or mitigation projects. Managers felt that their organizations were most likely to adapt to climate change through use of existing management strategies that are already widely implemented for other non-climate related management goals. Chapter 5 explores whether the boundary organization (workshops) and objects (climate change science products) used in the previous chapters were perceived as credible and useful. Perceived credibility and usefulness increased overall, and regional-scale hydrologic information was deemed most useful. We discuss the importance of uncertainty, visualization, and best practices for effective climate change deliberation at the research-management interface.

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CHAPTER 1

Dissertation overview

This dissertation focuses on the relation between earth and human systems through the lens of climate change in complex terrain with a particular focus on issues related to water availability. Complex, or mountainous, terrain offers a unique challenge to the localization of climate change science since elevation and topography strongly determine local climate. The biophysical complexities of this downscaling of climate-related data are explored through a historic-looking context within Chapter 2 (Klos et al., 2015) and through a future-looking context in Chapter 3 (Klos et al., 2014). The historic approach used in Chapter 2 attempts to use an interdisciplinary framework to evaluate climate-related data needs by Idaho end-users and compile the relevant datasets of existing climate-related data into documents that are accessible and understandable to both a scientific audience and general public (Klos et al., 2015). Chapter 3 (Klos et al., 2014) uses the assumption that the change of precipitation phase due to climate warming, from more snow to more rain, is of particular concern to people across the complex terrain of the western U.S. Chapter 3 uses the combination of existing datasets to analyze which areas of the western U.S. are rain- versus snow-dominated historically (late 20th Century), and how specifically (at 4 km resolution) these areas are projected to change by the middle of the 21st Century considering the complexities of local topography and its influence on local temperatures during days when precipitation is occurring (Klos et al., 2014).

Chapters 4 and 5 then summarize and evaluate the dissemination of climate-related datasets, including Chapter 2 and Chapter 3, to end-users within communities across Idaho and Montana through a series of one-day workshops. Chapter 4 (Kemp et al., 2015) uses a mixed-methods approach, including pre- and post-workshop surveys, interviews, and small-group deliberations to evaluate perceived usefulness, effectiveness of discussed adaption strategies, and barriers to implementation on public lands of the various types and scales of climate-related content covered in the workshops. Chapter 5 (Blades et al., 2016) provides a theoretical and practical overview of the workshops, describing their structure and evaluating individual components on their ability to help bridge the boundary between the management-focused and research-focused scientific communities. Chapter 5 evaluates what strategies of science communication were more or less effective for bridging this boundary and what new best practices may most help move forward similar types of science outreach.

Together Klos et al. (2015), Klos et al. (2014), Kemp et al. (2015), and Blades et al. (2016) offer a team-based interdisciplinary dissertation of the type intended by the primary funding source for the project, the National Science Foundation's Integrative Graduate Education and Research Traineeship. The synthesis and analysis of biophysical data from the earth and life sciences, dissemination of that data both within and beyond academic spheres, and finally the evaluation of that dissemination to advance theory within the social sciences, together offer an example useful to others pursuing similar interdisciplinary endeavors at the interface of education, research, and outreach.

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CHAPTER 2

Indicators of climate change in Idaho: An assessment framework for coupling biophysical change and social perception

P. Zion Klos, John T. Abatzoglou, Alycia Bean, Jarod Blades, Melissa A. Clark,
Megan Dodd, Troy E. Hall, Amanda Haruch, Philip E. Higuera, Joseph D. Holbrook,
Vincent S. Jansen, Kerry Kemp, Amber Lankford, Timothy E. Link, Troy Magney,
Arjan J. H. Meddens, Liza Mitchell, Brandon Moore, Penelope Morgan,
Beth A. Newingham, Ryan J. Niemeyer, Ben Soderquist, Alexis A. Suazo,
Kerri T. Vierling, Von Walden, and Chelsea Walsh

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Abstract

Climate change is well documented at the global scale, but local and regional changes are not as well understood. Finer, local- to regional-scale information is needed for creating specific, place-based planning and adaption efforts. Here the development of an indicator-focused climate change assessment in Idaho is described. This interdisciplinary framework couples end users' data needs with observed, biophysical changes at local to regional scales. An online statewide survey of natural resource professionals was conducted to assess the perceived impacts from climate change and determine the biophysical data needed to measure those impacts. Changes to water resources and wildfire risk were the highest areas of concern among resource professionals. Guided by the survey results, 15 biophysical indicator datasets were summarized that included direct climate metrics (e.g., air temperature) and indicators only partially influenced by climate (e.g.,wildfire).Quantitative changes in indicators were determined using time series analysis from1975 to 2010. Indicators displayed trends of varying likelihood over the analysis period, including increasing growing season length, increasing annual temperature, increasing forest area burned, changing mountain bluebird and lilac phenology, increasing precipitation intensity, earlier center of timing of streamflow, and decreased 1 April snowpack; changes in volumetric streamflow, salmon migration dates, and stream temperature displayed the least likelihood. A final conceptual framework derived from the social and biophysical data provides an interdisciplinary case example useful for consideration by others when choosing indicators at local to regional scales for climate change assessments.

Introduction

Global observations have shown recent increases in mean surface temperature, upper-ocean heat content, sea level, and atmospheric water vapor together with decreases in sea ice, snow-cover extent, and glacier volume that provide strong evidence of a warming planet (IPCC 2014). Scientific evidence demonstrates that climate change is primarily attributable to anthropogenic drivers (IPCC 2014). However, the relationships between atmospheric changes (e.g., precipitation, temperature) and the related impacts on human and natural systems are often hard to disentangle, particularly because these impacts are biophysically complex and only partially influenced by climate (USGCRP 2011b, 2012). Indicator-focused climate change assessments, which define climate change indicators as any time series variable useful for displaying the influence of changing climate over time, have been conducted from local to national spatial scales (e.g., Hayhoe et al. 2007; Pederson et al. 2010; Betts 2011; USGCRP 2011a; Blunden and Arndt 2013). Despite the diversity of indicator-focused studies, specific changes occurring within the inland northwest of the United States have not been synthesized, and no climate change assessment of indicators and data needs at an appropriate scale for Idaho end users currently exists.

End users represent a broad range of natural resource professionals, including those working for federal and state agencies, nongovernmental organizations, and other entities such as local governments or corporations. End-user engagement can inform scientific assessments and strengthen the overlap between societal need (e.g., perceived concerns, end-user data needs) and available climate-related data (biophysical indicators) to improve adaptation to climate-related impacts (Meyer 2012). Eliciting end users' input concerning their specific needs is especially important when empirical data are complex, uncertainty is prevalent, and the perspectives of end users are diverse (Moss et al. 2014). Studies have been conducted to explore perceptions of climate change and associated impacts, notably at national and regional scales (e.g., Hulme and Turnpenny 2004; Leiserowitz 2005; Leiserowitz and Smith 2010; Leiserowitz et al. 2011). Expert elicitation has also been sought for many climate change assessments seeking to provide salient information specifically tailored to end users (Cohen 1997; NRC 2010; EPA 2010; Craghan 2012; Melillo et al. 2014). Although end user and expert engagement has been conducted at national and regional scales, there is a need for targeted engagement at finer scales to address the needs of local end users.

Previous research shows that much of science is not used, or usable, by resource managers and decisionmakers (Sarewitz and Pielke 2007). There are a variety of reasons for this, including institutional expectations that vary between research entities and policy makers or land managers, but one of the core problems is researchers' failure to understand end users' needs. In the case of climate science, the situation is especially challenging because the variables that are easily tracked and highly responsive to climate change (e.g., temperature or phenology) are often not directly aligned with the issues of importance to those charged with managing resources and protecting human communities (Kiem and Austin 2013; Vera et al. 2010). For instance, local communities may desire to know how climate change may impact the spread of disease, yet there is considerable uncertainty about how and when such impacts may become realized. In response, there have been calls for incorporating end users in prioritizing information needs (Dilling and Lemos 2011).

Idaho serves as a regional case example of a state level political boundary with a diversity of end-user information needs regarding climate change. Idaho is distinctive in that it contains larger portions of federal land and designated wilderness (Gorte et al. 2012), as well as a lower overall population density (Mackun and Wilson, 2011), when compared to the national average. The heterogeneous nature of the landscape (e.g., forests, rangelands, and croplands), natural resource management, and climate across the state provide the opportunity to develop a template for an indicator-focused climate change assessment that overlaps available science with the data needs and climate concerns of its resource management community. Despite the diversity of end users with varied socioeconomic dependencies on natural resources, decisions commonly must be made within a unified political boundary (e.g., state level, regional management office, river basin treaty). This can create challenges for policy implementation, particularly when desired environmental policy actions are dependent on strong scientific understanding and high perceived risk (Lubell et al. 2006; Stoutenborough et al. 2013). To overcome this lack of specific knowledge and lack of perceived risk, local- to regional-scale assessments are needed to garner public support for collective action (Lubell et al. 2006; Stoutenborough et al. 2013).

In an effort to advance the broader science of climate change assessment and to provide detailed climate change information relevant to end users, we aim to 1) present our interdisciplinary framework for others seeking to choose and synthesize indicators for local to regional-level climate change assessments and 2) provide a proof-of-concept case example that incorporates both an exploration of social needs/concerns and data on biophysical indicators of climate change across the state of Idaho. Considering the complex interdisciplinary nature of the study, the following text does not follow a traditional format. Instead we first highlight the framework of our interdisciplinary approach, and then display the methods and results for each the social and biophysical aspects of our study individually, before finally concluding with an integrated discussion (Figure 1.1).

Interdisciplinary process

To develop a statewide indicator-focused assessment of climate change, we, an interdisciplinary team of social and biophysical scientists, conducted a statewide survey of natural resource managers and professionals to assess perceived impacts of climate change and explore what available biophysical data end users deemed most important for assessing climate impacts. We used the results to refine a set of climate-linked biophysical datasets as potential climate indicators. Based on survey results and data availability, we created the assessment framework for identifying potentially important climate change indicators. Indicators were defined as direct or near-direct climate metrics (e.g., temperature, precipitation) or were indirectly linked to climate (e.g., streamflow, wildfire, etc.). Using our prior process understanding, we placed indicators along a conceptual spectrum to qualify their differences in mechanistic relationship to direct climate variables, thus allowing us to highlight their biophysical complexity or level of difficulty involved in discerning trends related to anthropogenic climate change (Fig. 1). Within the conceptualization, variables (or direct metrics) that are closely linked to climate are toward the left side of the spectrum, whereas other variables that are only partially influenced by climate (being heavily controlled by other mechanisms as well, such as land management, ecological stressors, etc.) are placed farther toward the right side of the spectrum (Fig. 1). Biophysical complexity, in relation to climate, increases toward the right of the spectrum, as the alternative biophysical nonclimatic controls compound and additionally influence the final dependent variable.

To highlight the findings and broadly share them with other interested groups, the research team created both this manuscript and complementary outreach documents, which were rewritten and organized to be easily accessible and appealing to the general public. These secondary documents contain common language, reworked graphics, and aesthetic aspects suggested and edited by the communication specialists on the team. They include an executive summary, detailed report/ booklet, website, and a pamphlet, the latter designed for distribution across Idaho. With approval of this manuscript and its findings by the peer-review process, these accompanying materials exist freely to the public through the University of Idaho.

Statewide climate-needs survey

Survey methods

Given the calls in the literature to engage stakeholders and end users in identifying science needs, our first step was to solicit input from individuals affiliated with some aspect of natural resource management in Idaho. Many of the proposed solutions are time and resource intensive, such as establishing boundary organizations or structured knowledge networks. In this paper, we adopted a relatively inexpensive, efficient approach to enhancing the connection between science and end users through the use of an online survey of key informants in Idaho. McKenna and Main (2013) articulate the value of using key informants to obtain expert information related to a community's needs; one recent example can be found in Berndtson et al. (2007), where researchers developed lists of potential study participants from staff recommendations, the literature, and snowball sampling to help identify grand challenges in public health.

An online survey was administered in February 2012 to evaluate which climate indicators were of primary concern to end users and which indicator datasets would be the most useful in their jobs (see the supplemental material, available at http://dx.doi.org/10.1175/WCASD- 13-00070.s1, for a copy of the survey). Using a purposeful (Coyne 1997) and snowball sampling approach (Creswell 2009), we obtained participant contact information from agency and organizational websites, and asked survey participants to provide contact information for other potential participants, or to forward the online survey directly to their colleagues. Ritchie et al. (2003) recommend purposive sampling as appropriate when the sample is intended to represent individuals who meet key selection criteria, and they note that this approach helps ensure that all key groups are included. We specifically sought individuals who would be in a position to comment on the utility of climate science to management or policy decisions. Additionally, our selection criteria were attentive to covering the full suite of professions (natural resource managers, specialists, and community leaders) that would ultimately use the final products of this indicator-based assessment in their work, in a form of maximum variation sampling (Sandelowski 1995). Thus, our sampling approach is most appropriately characterized as what Patton (1990) calls stratified purposeful sampling, designed to achieve coverage of all groups. A total of 612 individuals were asked to participate. Participants included individuals working for state agencies (37%), federal agencies (32%), nongovernmental organizations (21%), and other entities (8%, corporate or private, and local governments).

The Internet survey was developed online using Qualtrics software and followed a modified Dillman method (Dillman et al. 2009), where participants were invited to participate through a work e-mail address and two weeks later received a reminder e-mail. The survey format included sequential questions about 1) perceived importance of climate change impacts within the state with a focus on natural hazards and social change and 2) indicators of climate changemost desired for assessment within five designated systems: water, forest, rangeland, agricultural, and social systems. The survey first asked participants about their personal concern regarding a broad range of climate impacts, and then asked about relevance of climate data to their jobs in an attempt to avoid an order effect, which could have caused participants to answer all questions with respect to their work interests and induce undesired priming (Salancik 1984). Within the first part of the survey, all respondents were asked to choose up to five impacts they were personally concerned about from a broad set of possibilities. The specific options within this broad set were designed to be far reaching in scope, but may have inadvertently primed the participants to focus their future answers only within the constructs of the impact options provided. Next they were asked to choose up to three responses (of the 12 possible, with three additional open-ended options) regarding direct measures of climate (i.e., direct temperature and precipitation metrics) they found most relevant to their job. They were then asked to choose one of the five designated systems (i.e., water, forest, rangeland, agricultural, social) that was most relevant to their job. This choice took them to one of the five possible subpages (one per designated system) where they could choose the top three indicators of the 12 or more options within that system. They were then asked if another one of the five designated systems was relevant to their job. If so, they were then directed to that designated system's subpage to again choose their top three most relevant indicators. After two (at most) designated system subpages the participants were then directed to the conclusion of the survey. The decision to limit respondents to no more than two systems was based on a need to minimize the burden on respondents, as the lists of indicators were quite long and because—given the breadth of respondents—we recognized that not all systems would be primarily important to all respondents.

We developed the survey questions collaboratively as a research group, with each discipline represented (e.g., hydrology, ecology, etc.), generating a comprehensive list of climate measures, potential impacts, and indicators that were considered most salient to each system and reflected the focus of similar work in other regions (Pederson et al. 2010; Betts 2011; USGCRP 2011a,b, 2012).

Summary of survey findings

A total of 100 surveys were completed, with respondent demographics mirroring those in the total population surveyed (Fig. 2). The top four concerns regarding climate change impacts were water resource availability (16% of respondents), extreme drought (14%), changes in plant productivity (14%), and wildland fire (10%; Fig. 2). Regardless of participant sector, concerns about biophysical impacts were consistently rated as the highest importance, and concerns about recreation and transportation impacts were rated as the lowest importance.

Based on a metric of ‘‘normalized importance,’’ which is defined as the number of times an indicator was selected by an individual end user divided by the total number of selections within a system, participants identified precipitation indicators as being the top three most useful climate measures: annual rainfall versus snowfall (23%), seasonality trends (22%), and general precipitation (14%; Fig. 3). Of all responses, 43% represented water-related occupational specialties as indicated by the choice of system specialties (Fig. 3). The top indicators for end users who selected the water resources system were streamflow timing, annual volumetric stream discharge, and stream baseflow discharge. Participants who selected the forest system focused on wildland fire severity and vegetation/wildlife distributions. Rangeland participants focused on vegetation indicators (i.e., plant productivity, vegetation distribution, and plant phenology). Agricultural participants focused on precipitation patterns, drought characteristics, and growing season length as their top priorities. Participants working with social systems selected water-based recreation, timing of peak visitation, and recreation restrictions due to wildland fire as the top climate change–related indicators.

Overall, participants were most concerned with water related impacts resulting from climate change and considered information about water resources availability to be the most important measures of climate change that were relevant and useful for their needs (Fig. 2). The topics of fire and vegetation were also top areas of participant interest. The occurrence and impacts of wildland fire ranked fourth for participant concern (Fig. 2), and indicators related to fire were among the top four most relevant in forest, rangeland, and social systems (Fig. 3). The impact of climate change on plant productivity and growth rates ranked third for participant concern overall (Fig. 2).

Statewide climate change indicators

Biophysical data selection

Biophysical indicators of climate change were identified based on existing datasets and results from the end user survey. After the survey results were acquired, the final indicators were chosen based on a criterion of both high interest to end users, as indicated by the survey results, and available data. Indicators were classified into three categories: climatological, hydrological, and ecological. A comparative analysis of climate-related trends was conducted over the time period of 1975–2010, as 1) it covers the period of most noted anthropogenic forcing and increases in global mean temperature (e.g., Lean 2010), 2) most indicators have complete data over this time span, and 3) the prominent modes of regional climate variability that influence the U.S. Pacific Northwest, such as El Niño–Southern Oscillation (ENSO), the Pacific–North American pattern (PNA), and the Pacific decadal oscillation (PDO), did not exhibit any significant long-term trends during this time period. Independent decadal-scale trends in these modes of climate variability have altered the pace of warming regionally and thus partially influence changes observed in climaterelated indicators, such as mountain snowpack (e.g., Mote 2006; Abatzoglou 2011; Abatzoglou et al. 2014b). To avoid selecting a time span that included a pronounced trend in regional climate variability, an ordinary least squares linear trend analysis was performed on mean annual PDO, PNA, and ENSO indices (Multivariable El Niño Index; Wolter and Timlin 1993) over variable time periods beginning in years 1950–85 and ending in 2010. Significant trends for these individual climate indices were identified for analyses starting prior to 1954 and after 1976. The 1975 start date was therefore selected to minimize the contribution of trends arising from internal climate variability and maximize the number of climate indictors for which datasets were available. For graphic representation, the baseline period from which anomalies were plotted against is 1971– 2000, except where otherwise noted, due to sparse data (e.g., phenology).

Statistical methods of trend analysis

We estimated the significance and strength of trends in climate indicators from 1975 to 2010 using ordinary least squares linear regression. This approach allowed us to evaluate the relative strength of each independent climate indicator over the chosen time frame. We then qualitatively ranked the climate indicators according to the strength of their trends to demonstrate how well they relate to general trends of regional to global anthropogenic warming over the same time period. All indicator variables were tested to ensure they met the assumptions of an ordinary least squares regression, including that the distribution of each set of data followed a normal distribution with constant variances and that all of the observations were independent. To test the normality of each set of data, we used a Kolmogorov– Smirnov goodness-of-fit test (Gotelli and Ellison 2004); annual area burned was the only time series that did not pass this goodness-of-fit test and was thus logtransformed to meet the assumption of normality, as commonly done when analyzing annual area burned data (e.g., Collins et al. 2006). Furthermore, since time series with significant autocorrelation (e.g., nonindependent observations) are more likely to show linear trends through time, we assessed autocorrelation in each time series using the Durban–Watson statistic and the 95% confidence interval (CI) around the autocorrelation function for years 1–5, following Diggle et al. (2002). If either the Durban–Watson test was significant or any of the 95% CIs for lag 1–5 autocorrelation did not overlap 0 (i.e., no autocorrelation), we estimated the true probability that the slope (ß1) parameter in each regression did not equal 0 using a block-resampling bootstrap technique repeated 10 000 times [adapted from methods in Gavin et al. (2011)]. The block size for resampling was set equal to the largest lag with significant autocorrelation for a given time series, and the true p value (p_auto) was estimated by comparing the observed ß1 parameter to the distribution of ß1 parameters from the 10 000 bootstrap samples. All reported p values assume an a priori one-tailed hypothesis test that the slope of the regression was different than zero. For slope analysis, the direction and strength of trends are only reported for significant ($p < 0.05$) and nonsignificant trends where $p < 0.20$. No slope is reported for trends with the lowest levels of confidence ($p > 0.20$).

Indicator data sources and methods

Time series data were acquired from diverse locations across Idaho to provide an integrated view of the state (Fig. 4). Temporally, datasets are displayed for their entire period of observation (Figs. 5–10), but time series trend analysis was only conducted over the 1975–2010 time period. Spatially, some datasets (e.g., temperature, precipitation, snowpack, burned area) are derived from a large number of observation sites and therefore have higher representation, while other data sources are less spatially representative of the state, such as stream temperature. Despite the shortcomings of spatial extent, these datasets were still included for analysis and discussion because they are the only long term data available for the desired variables within the state.

Data sources and methods for direct climate metrics

Daily maximum and minimum temperature and precipitation from the 29 U.S. Historical Climate Network (USHCN) stations located within Idaho (Fig. 4) were acquired for their period of record evaluated using quality assurance and control measures (Menne et al. 2009). Growing-season length, defined as the number of days between the last day in spring with overnight low temperatures below 08C and the first autumn day with low temperatures below 08C, was calculated for each station. However, because of spatial disconnect from agriculture, we narrowed our analysis for growingseason length to 12 stations below 1807m in elevation and missing less than 10% of daily observations. Growing-season length for individual stations was normalized over a common 1971–2000 reference time period. This normalization period was chosen because complete data were available from all stations, thus eliminating the influence of varying means and standard deviations across stations with nonconcurrent records. For each year we estimated the statewide-standardized anomaly based on the mean from all reporting stations.

For precipitation intensity, the largest single-day of accumulated precipitation annually and for the spring season [1 March–31 May (MAM)] was used [similar to Osborn et al. (2000)]. While all seasons are of interest, we identified spring as the most important for Idaho end users because of the high potential for saturated soil water content, runoff, and erosion (Williams et al. 2001). Data were compiled from time periods in which .15 of all the USHCN stations in Idaho had .80% of the data during a given spring (1920–2012). The deviation of the maximum one-day precipitation event from the mean of the analysis period (%) was computed and averaged across the stations. This synthesized change was normalized by the 1971–2000 time period using the median maximum precipitation amount for each station.

For snowpack, we compiled a long-term dataset of snow course records collected by the Natural Resources Conservation Service (NRCS) Water and Climate Center. A total of 126 locations in Idaho contained 1 April snow water equivalent (SWE) data for every year from 1975 to 2011. These data were normalized to the entire dataset within each site during the 1975–2011 period and these normalized values for each year were averaged across all 126 sites for a final statewide mean value for each year.

Hydrologic data sources and methods

Daily streamflow data were obtained from the United States Geological Survey (USGS) Hydro-Climatic Data Network for 26 gauges on watersheds that have experienced minimal land-use change, a low amount of human influence, and negligible water diversion from 1950 to 2005 [for specifics, see Slack and Landwehr (1992) and Clark (2010)], thus allowing for the influence of climate change to more easily be isolated from the other methods of anthropogenic forcing. To create a statewide aggregated assessment of flow changes, data were averaged across all stations. For average stream temperature, daily records were used from the USGS gauge at the Canyon Ranger Station on the North Fork of the Clearwater River within north-central Idaho (Fig. 4). These records have been kept since 1971, and they provide a uniquely long-term and robust stream temperature dataset within Idaho. Records from this site have been used previously to examine climate change impacts on stream temperature and salmonids (Isaak et al. 2012).

Ecological data sources and methods

Records of lilac (Syringa vulgaris) first bloom dates were acquired from the North American First Leaf and First Bloom Database, which contains observations collected by citizen scientists (USA National Phenology Network; Schwartz and Caprio 2003). From the database, we selected 13 monitoring sites in Idaho with at least 20 years of records from 1957 to 1993. Standardized anomalies of statewide first bloom data were estimated by calculating the average and standard deviation for the first 22 years of the record (1957–78, during the highest density of reported data), computing standardized bloom date anomalies for each station and year, and averaging all reporting sites within a given year.

Citizen scientists also collected bird nest phenology data. Nest phenology of the Mountain Bluebird (Sialia currucoides), Idaho's state bird, was collected by a citizen scientist who has examined nests and banded birds using bluebird nest boxes for approximately 30 years in southwestern Idaho, and who is certified by a Master Banding Permit issued by the Bird Banding Laboratory at the USGS (A. Larson 2012, personal communication). Nest records included year, number of eggs, number of eggs hatched, hatch date, and number fledged; these data span a temporal period of 1992–2006, 2009, and 2011 with 9–19 observations per year (n 5 17). It was assumed that one egg was laid per day, which is true for nearly all songbirds, and that the incubation period was 13 days (Power 1966; Power and Lombardo 1996). Following Dunn and Winkler (1999) and Dolenec et al. (2011), we used these data to back-calculate to first egg date (i.e., first egg date 5 hatch date2132number of eggs). April temperature data were acquired from the National Climatic Data Center for the weather station at Arrowrock Dam; 82% of nest initiations occurred in April. We were unable to conduct time series trend analysis because of the low number of observation years; thus, we used linear regression to examine the relationship between nesting date and temperature. FIG. 8. Hydrologic indicators: (a) mean day of calendar year for center of timing of streamflow across 26 stations in Idaho, (b) mean water-year volumetric flow in a thousand cubic feet per second across the same 26 stations, and (c) annual mean stream temperature for the North Fork Clearwater River, north-central Idaho. See Fig. 4 for station locations. The horizontal line is the 1971–2000 mean for each dataset. FIG. 9. Phenology indicators: (a) mean statewide (variable number of sites) day of year for first bloom of lilac relative to the average 1957–78 normal (mean of the analysis period), (b) median date of upstream adult sockeye salmon migration as recorded (gray 5 missing data) at Lower Granite Dam, the uppermost dam on the lower Snake River near the Washington/Idaho border, and (c) linear regression of mountain bluebird earliest and median egg date as a function of mean April temperatures; data (n 5 17) are from locations near Arrowrock Dam, Elmore County, Idaho, from 1992–2006, 2009, and 2011.

Phenological data also included the median date of summertime upstream migration for adult sockeye salmon (Oncorhynchus nerka). Fish count records, provided by the Columbia River Data Access in Real Time program, were acquired from 1975 to 2011 from Lower Granite Dam (the uppermost dam on the lower Snake River).

Although this site is just outside of the state boundary, the vast majority of the upstream drainages it encapsulates are within Idaho (Fig. 4).

We analyzed updated fire-perimeter data from 1902– 2009 that account for forest fires >0.5 ha on federally managed forest lands to examine trends in forest area burned by wildland fire within Idaho. This dataset comprises continuous values (decimal ha) for area burned and meets the assumptions for the ordinary least squares statistical analysis. Additionally, discovery dates from all large wildland fires (>400 ha) within the state (forested and nonforested) from 1984 to 2009 were obtained from the Monitoring Trends in Burn Severity Project. We used the discovery date of the first (early season) and last (late season) fire as a proxy for estimating the length of the summer fire season.

Indicator results from climate observations

Temperature and growing season

End users exhibited limited interest in mean annual temperature, likely due to its lack of direct impact to the end users. However, mean annual temperature is mechanistically linked to numerous indicators with much higher perceived impact and has served as a hallmark global climate indicator. Historically, mean annual temperature in Idaho shows a nonmonotonic increase, with the last two decades being the warmest on record (1894– 2010, Fig. 5a). The 1975–2010 trend analysis revealed a warming trend of 0.248Cdecade21 (p 5 0.01, Table 1), similar to that observed for the broader Pacific Northwest (Abatzoglou et al. 2014b).

Growing season length was among the top indicators desired by survey participants. The growing season in Idaho has increased over the entire period of record (1918–2010, Fig. 5b) with an increase of 3.9 days decade21 from 1975– 2010 (p 5 0.01, Table 1). These results are consistent with observations across the Pacific Northwest (Abatzoglou et al. 2014b) and broader United States (Easterling 2002; Vose et al. 2005) and may be explained by increased overnight temperatures during the spring and autumn.

Precipitation intensity

The largest single-day precipitation total in spring (MAM) increased by 5.1% decade21 over the 1975– 2010 period (p 5 0.06, Fig. 6, Table 1). Data across the state also suggest that the largest single-day annual precipitation amount increased 2.9% decade21 over the 1975–2010 period (p 5 0.19, Table 1). This is similar to findings that total precipitation over the contiguous United States has increased from 1910 to 1996, with 53% of the increase coming from the most intense (upper 10%) of precipitation events (Karl and Knight 1998).

Snowpack

The statewide average 1 April snow-water equivalent showed a long-term decrease (Fig. 7). Most notably, this decline is seen over the latter half of the twentieth century, which mirrors trends across the western United States (e.g., Mote et al. 2005). However, decreases in SWE of 4.4% decade21 from 1975–2010 were not significant (p 5 0.16, Table 1) in Idaho. Similarly, trends in the fraction of precipitation falling as snow in the Owyhee Mountains of southwestern Idaho have shown decreases over the last several decades (Nayak et al. 2010). This decrease in the percentage of annual precipitation occurring as snowfall is consistent with similar trends across the western United States since 1950 (e.g., Knowles et al. 2006; Abatzoglou 2011)

Indicator results from hydrologic systems

Streamflow

Statewide, the center of timing (CT) for streamflow, which is defined as the day of the year when 50% of the water-year's streamflow has occurred, advanced from 1950 to 2005 (Fig. 8a, Table 1). Total volumetric wateryear streamflow decreased during the 1950–2005 period (Fig. 8b, Table 1), similar to what others have found (Luce and Holden 2009; Clark 2010). For the shorter time period of analysis from 1975 to 2010, the CT of streamflow was 1.9 days earlier per decade (p 5 0.14, Table 1). No trend was observed for volumetric wateryear streamflow from 1975 to 2010 after accounting for autocorrelation (p_auto 5 0.43). Since interannual variability in volumetric streamflow is closely linked to annual precipitation across the region (Abatzoglou et al. 2014a), it is subject to high interannual variability not directly associated with rising temperatures, making trends hard to detect within this 35-yr analysis period. Additionally, as some subbasins exist at higher and lower elevations, the influence of the transition from snow to rain over time will have a varying effect on the landscape that may be difficult to detect in this statewide-integrated analysis.

Stream temperature

Mean annual stream temperature increased approximately 0.148Cdecade21, with a total increase of 0.558C over the 1970–2011 period of record (Fig. 8c, Table 1). When analyzed over the only period of available nearcontinuous data from 1987 to 2010, no significant trend was found for stream temperature changes (p 5 0.49, Table 1). Since stream temperature is influenced not only by atmospheric conditions (e.g., solar radiation, air temperature, precipitation), but also by streamflow (discharge, friction, turbulence), physiography (slope, aspect, elevation, geology, riparian vegetation), and streambed properties (sediment, hyporheic exchange, groundwater), this make trends due to climatic drivers more challenging to detect (Caissie 2006).

Indicator results from ecological systems

Phenology

Lilacs bloomed increasingly earlier from 1957 to 1993 (Fig. 9a, Table 1). Over the period of trend analysis (1975–93), lilacs bloomed 8.1 days earlier per decade (p 5 0.02), similar to elsewhere in the United States (Cayan et al. 2001; Schwartz et al. 2006; Betts 2011). In contrast, there was no change in timing of salmon upstream migration from 1975 to 2010 once we accounted for autocorrelation (p_auto 5 0.40; Fig. 9b, Table 1). Timing of salmon migration is indirectly affected by climate via stream temperature and changes in the seasonal duration and intensity of flow regimes, but is also controlled by other ecological factors (McCullough 1999; Crozier and Zabel 2006). Therefore, any relationship may be difficult to detect.

For mountain bluebirds, earliest and median egg dates were related directly to mean April temperatures near the site (Fig. 9c). For every 18C increase in mean April temperature, the earliest egg date was approximately 4 days earlier (p < 0.01, R2 5 0.45) and the median egg date was approximately 3 days earlier (p 5 0.01, R2 5 0.34). These results corroborate other analyses of nest initiation and temperature (Dunn and Winkler 1999; Dolenec and Dolenec 2011; Dolenec et al. 2011).

Wildland fire

In Idaho, more forest area burned early (1910–35) and late (1984–2009) than in the middle of the twentieth century (Fig. 10a, Table 1; see Morgan et al. 2008).During

1975–2009, area burned increased by 43 000 ha decade21 across Idaho forests (p_auto 5 0.01). The discovery date of the last large fire each year (>404 ha) was delayed by 9.2 days decade21 (p 5 0.07, Fig. 10b, Table 1) over the 1984–2009 analysis period of available data. In contrast, no trend was observed in early fire season discovery dates (p_auto 5 0.27, Fig. 10b, Table 1). When the annual length of the fire season is calculated by using both the earliest and latest discovery dates as the annual starting and end points, fire seasons are becoming longer by approximately 19 days decade21 in forests over the past 25 years (Fig. 10b).

Summary of indicator findings

We found significant statewide trends ($p < 0.05$) for several indicators over the 1975–2010 period (Table 1). Mean annual air temperature has increased, growing seasons have become longer, lilacs have bloomed earlier, and more forest area has burned over time. We identified additional nonsignificant trends with lower levels of confidence ($0.05 < p < 0.17$) indicating higher maximum daily spring precipitation, earlier peak streamflow, decreased 1 April SWE, and a longer fire season measured as the late season fire discovery date (Table 1). In contrast, other indicators, including annual volumetric streamflow, timing of sockeye salmon migration, mean annual stream temperature, and early season fire discovery date, did not exhibit detectable trends from 1975 to 2010 ($p > 0.26$; Table 1). The lack of a trend in these latter indicators does not necessarily mean they are insensitive to anthropogenic warming. Alternatively, the possibility exists that 1) controlling factors aside from temperature are important drivers of these variables and/or 2) the observational period 1975–2010 was too short and the interannual variability too large to exhibit a strong change over the period of record.

The cumulative effects of climate change are expected to be various and compounded, particularly in some years due to extreme events. This interannual variability and extremes may be more important to some end users than mean values. For instance, in 2000, 2003, and 2007, fires were so widespread in Idaho that lives and property were widely threatened, costs of fire suppression were high, and both national and state firefighting resources were nearly inadequate to meet demands. The coincidence of extreme values for other indicators makes such years more challenging for natural resource management. In the same years (2000, 2003, and 2007) annual temperatures were high, the growing season was long, spring precipitation was low, 1 April SWE was low, peak streamflow was early, volumetric streamflow was low, stream temperatures were high, and the fire season extended late into the fall (Figs. 5–10). These combined effects can adversely impact ecosystems, recreation, and other ecosystem goods and services.

Statewide synthesis of survey and indicator findings

End users, including natural resource professionals and decision makers in Idaho, seek a variety of climate change assessment information. Of the top four climate change impacts highlighted by survey respondents (water availability, drought, plant productivity, and wildland fire), we were only able to obtain historical data to address water availability, drought, and wildland fire. First, the timing of in-stream water availability advanced with the CT of streamflow moving earlier into the year, especially when the observed 1 April SWE is low. Although we detected no trend in annual water-year volumetric streamflow from 1975 to 2005, longer-term trends from other studies (which include pre-1975 data) suggest a significant decrease in the volume of annual streamflow (Luce and Holden 2009; Clark 2010; Luce et al. 2013). Second, annual forest area burned increased over the 1975–2010 time period and the length of the wildfire season has increased by over a month. Unlike water- and fire-related impacts, readily available historical time series datasets for plant productivity information were not found within the state.

The top three direct measures of climate desired by respondents were precipitation focused. Our biophysical findings addressed respondent interests about precipitation trends through analysis focused on changes in extremes. Results indicate increases in intensity of precipitation, with the highest increase in the intensity of spring precipitation over the 1975–2010 period statewide.

Despite the diverse data reported here, gaps remain. First, we lack information about several other key variables identified by end users within Idaho, including distribution of plant and animal species and timing of outdoor recreation windows. Spatial resolution could also be improved for the biophysical datasets derived from only one location (e.g., stream temperature, etc.) through increased monitoring programs, some of which are already underway but currently lack long-term records (Isaak et al. 2012).

In this paper, we demonstrate the utility of involving stakeholders in identifying climate-related information needs through a low-cost, efficient tool. If more precision and greater ability to generalize to a population are desired, this technique could easily be expanded to include random samples of populations of interest. Despite these limitations, pairing key end-user needs with a wide range of available biophysical data provides an example of a novel interdisciplinary framework for indicator-focused climate change assessments.

Advancing an interdisciplinary assessment framework

With rapid biophysical changes occurring across Idaho and the globe, policy makers and land managers are increasingly seeking to understand the effects of our changing climate. The inherent uncertainty, lack of immediacy, and current paucity of evidence of direct impacts of climate change can impede effective communication between land managers and the public regarding the anticipated changes and potential management options (Moser 2010). Effective action depends on understanding regional and local implications of climate science through an interdisciplinary lens that accounts for the needs of end users, who range from city water managers to wildlife professionals. Thus, we provide this interdisciplinary case example for indicator-focused climate change assessment. We use Idaho-specific climate change science and a survey of end-user needs as a clear and targeted case example that highlights the topics that our intended audience is shown to value and understand (Nisbet and Kotcher 2009), improving the likelihood of both end-user acceptance and use of the science for policy and management decisions.

Using biophysical climate indicators to assess the impacts of climate change is difficult because of their varying levels of control by direct climate metrics (i.e., changes in temperature and precipitation). This level of control, or biophysical complexity in relation to climate, reflects the degree to which indicators are mechanistically controlled by, and therefore reflective of, regional climate. When choosing indicators for this local-to-regional scale climate change assessment, the perceived importance (i.e., perceived climate change impacts and data needs) of the indicator datasets to eventual end users was considered so as to make the final product (i.e., the regional climate change assessment) as useful as possible. This type of approach—using key informants to screen indicators for their utility—enhances the likelihood that science will inform and improve future resource management.

Our survey results qualitatively indicate differences in the perceived importance of certain indicators over others from the perspective of end users (y axis of Fig. 11, derived from Fig. 2 and 3), whereas the biophysical complexity of an indicator (x axis of Fig. 11, derived from Fig. 1) is related to the relative influence of direct climate forcings (e.g., temperature) versus other, non-climate-related, mechanisms (e.g., ecological competition, human manipulation) controlling the variable. Within this two-dimensional conceptualization, indicators can be delineated into four quadrants that can help others conceptualize social and biophysical trade-offs when evaluating an indicator for possible inclusion in a climate assessment (Fig. 11).

In this case, indicators grouped within the zone of highest perceived importance and lowest biophysical complexity are snowpack, streamflow, drought, and precipitation. These likely rank high in perceived importance because they are linked to water limitations and—since under a warming global climate, water limitation is of much higher concern than energy limitation— these indicators are some of the most important to end users in water-limited regions, such as our Idaho case example. Furthermore, indicators that are low in perceived importance and low in biophysical complexity (e.g., temperature metrics) are biophysical variables that people may have little control to impact locally; although extreme levels of air temperature and stream temperature may be of concern, a general warming trend is of much less perceived importance to end users than issues of water limitation within our case example. However, in other regions (e.g., desert cities with urban heat islands), results of such analysis might reveal temperature increase as being of high perceived importance.

Indicators high in both perceived importance and biophysical complexity (fire and productivity related) are likely of higher perceived importance to people because they are tangibly visible and potentially harmful (e.g., destruction of land/property or loss of food). In addition, on account of the high level of biophysical complexity these types of indicators are some of the greatest challenges for the research community to assess in relation to climate. Therefore, more research effort needs to be devoted to understanding how they are likely to be impacted by climate change, while also considering other controls beyond climate (e.g., fuel loading, land management, global economics, ecological drivers).

This basic framework developed through our Idaho case example, along with national-scale insights (USGCRP 2011a), will help others as they decide how to create local- to-regional-scale climate change assessments that overlap social importance with biophysical changes. By surveying the relevant end users, the types of variables available and most pertinent to them can be considered in conjunction with their level of complexity connecting the biophysical variable to climate. With the use of such a framework and engagement of end users from the onset, local- to regional-scale climate change assessments worldwide can strongly increase the likelihood that they are applied by the people making critical decisions that shape and prepare their landscapes for the future.

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Tables

Table 2.1. Summary of trend likelihood, slope, and R^2 for linear regression analyses of biophysical climate change indicators within Idaho, USA. Ranked by level of trend likelihood with indications for **significant** (**bold**, $p < 0.05$) and non-significant ($p > 0.05$).

Time Series within Idaho (1975-2010)	***p Value*** *(*p_auto)*	***Change per Decade***	R^2
Growing Season Length	**0.01**	**3.9 days longer**	**0.17**
Mean Annual Temperature	**0.01**	**0.24 °C warmer**	**0.13**
Annual Forest Area Burned (log. transformed)	**0.01***	**43,000 hectares more**	**0.24**
Lilac Bloom Dates	**0.02**	**8.1 days earlier**	**0.22**
Extreme Precipitation - Spring	0.06	5.1 % greater	0.07
Late Fire Season Start Date (1984-2009)	0.07	9.2 days later	0.09
Streamflow - Center of Timing	0.14	1.9 days earlier	0.04
Snowpack - April 1 SWE	0.16	4.4 % less	0.03
Extreme Precipitation - Annual	0.19*	2.9 % greater	0.06
Early Fire Season Start Date (1984-2009)	0.27*	-	0.01
Salmon Migration Dates	0.40*	-	0.04
Streamflow - Annual Volume	0.43*	-	0.03
Stream Temperature (1987-2011)	0.49	-	0

Figures

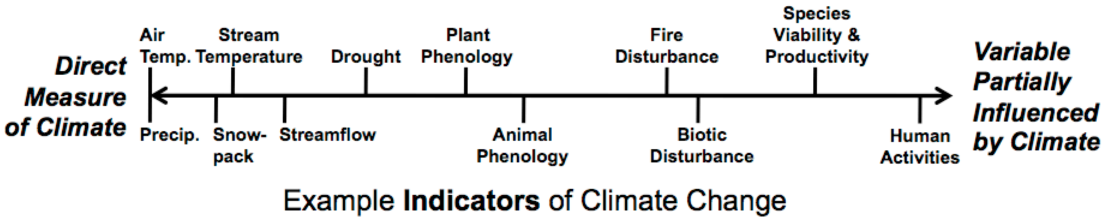


Figure 2.1. Indicators of climate change across a conceptual spectrum from direct climate metrics to variables partially influenced by climate.

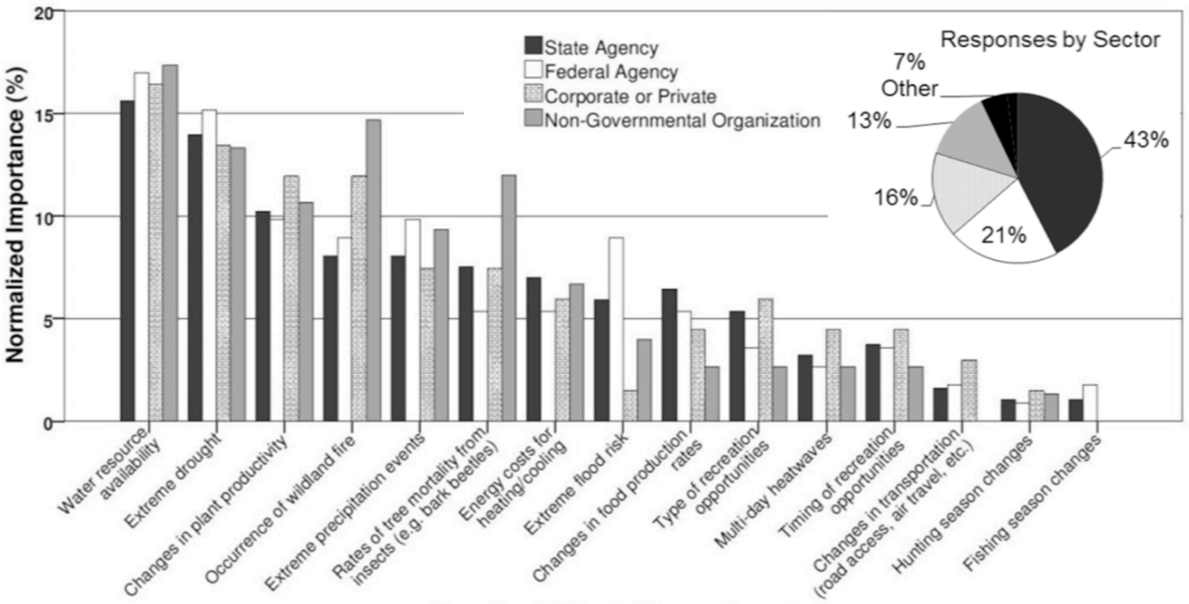


Figure 2.2. Perceived importance of climate change *impacts* in Idaho, USA by end-users. Responses (n = 440) are stratified by sector of the respondent: state agency, federal agency, corporate or private, or non-governmental organization (with the “other” category removed due to small sample size). The response rates of each sector are shown top right. “Normalized Importance” is the number of times an impact was selected by an individual end-user divided by the total number of selections within a sector.

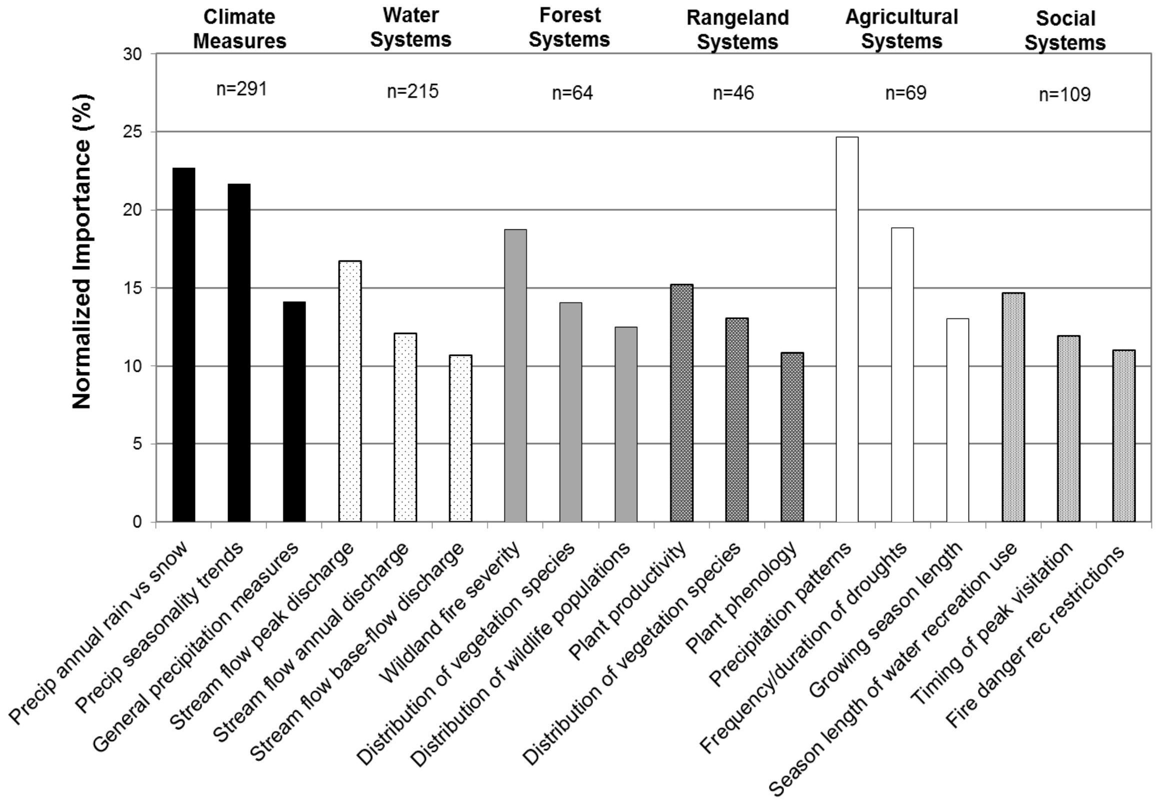


Figure 2.3. Climate change *indicators* that participants reported would be most useful within their work, pooled across all stakeholder types and segregated by natural resource system (top three per system are shown). "Normalized Importance" is the number of times an indicator was selected by an individual end-user divided by the total number of selections within a system.

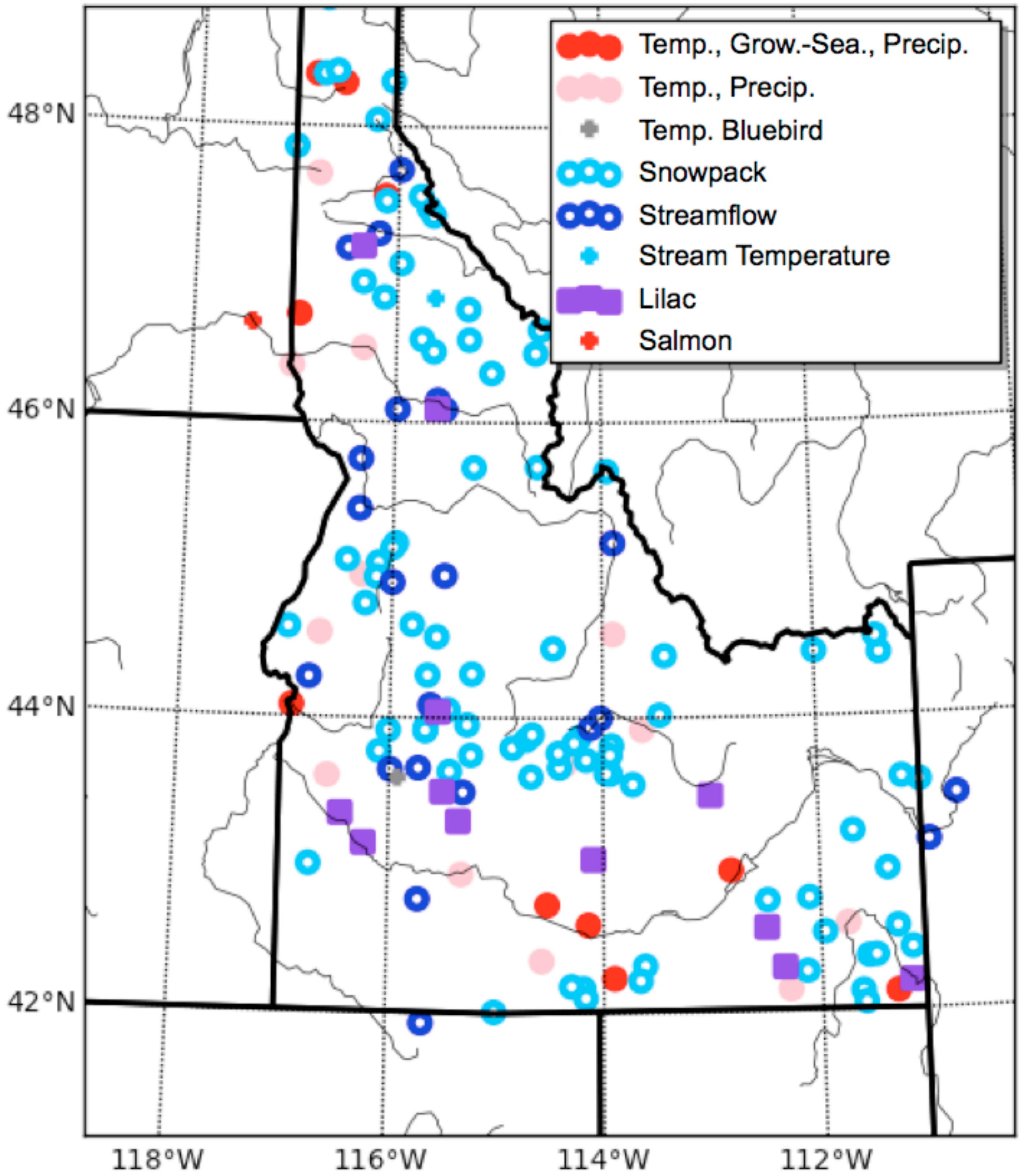
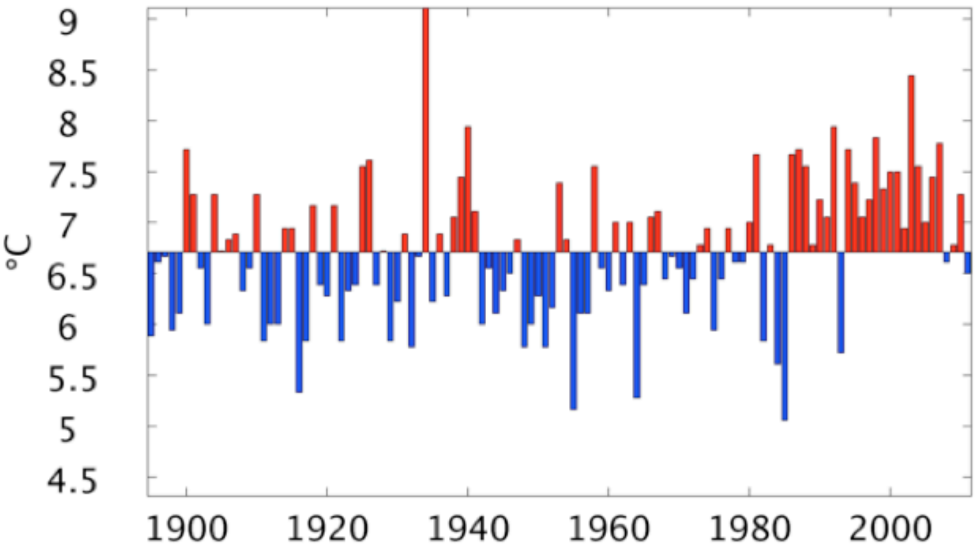


Figure 2.4. Locations of point-source biophysical indicator data within Idaho, USA. Distributed wildland fire data were aggregated across the entire state.

(a) Mean Annual Temperature



(b) Growing-Season Length

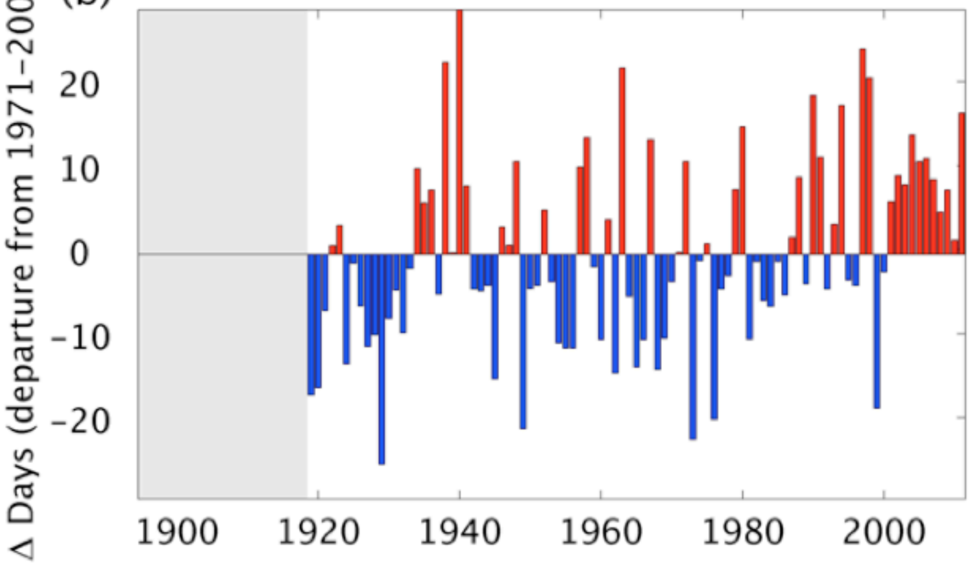


Figure 2.5. Temperature indicators: **5a**) Mean annual temperature across Idaho, USA (n = 29 stations), and **5b**) Departures from mean (1971-2000) growing season length as indicated by number of growing-season days across 12 stations in Idaho, USA (see Figure 4 for locations).

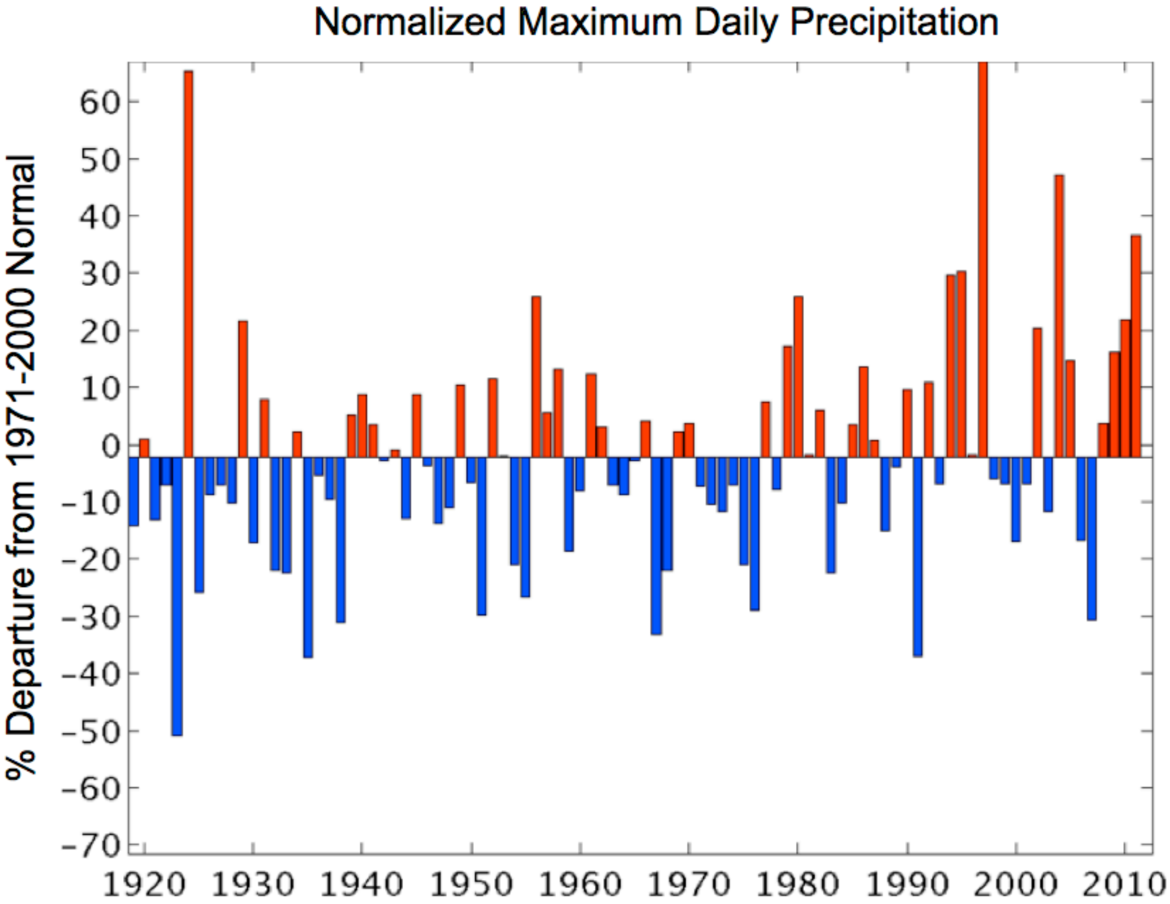


Figure 2.6. Precipitation indicator: Intensity of the most extreme one-day precipitation event of the spring (March, April, May) in a given year relative to the mean from 1971-2000 (normal) for 28 stations in Idaho, USA (see Fig. 4 for locations).

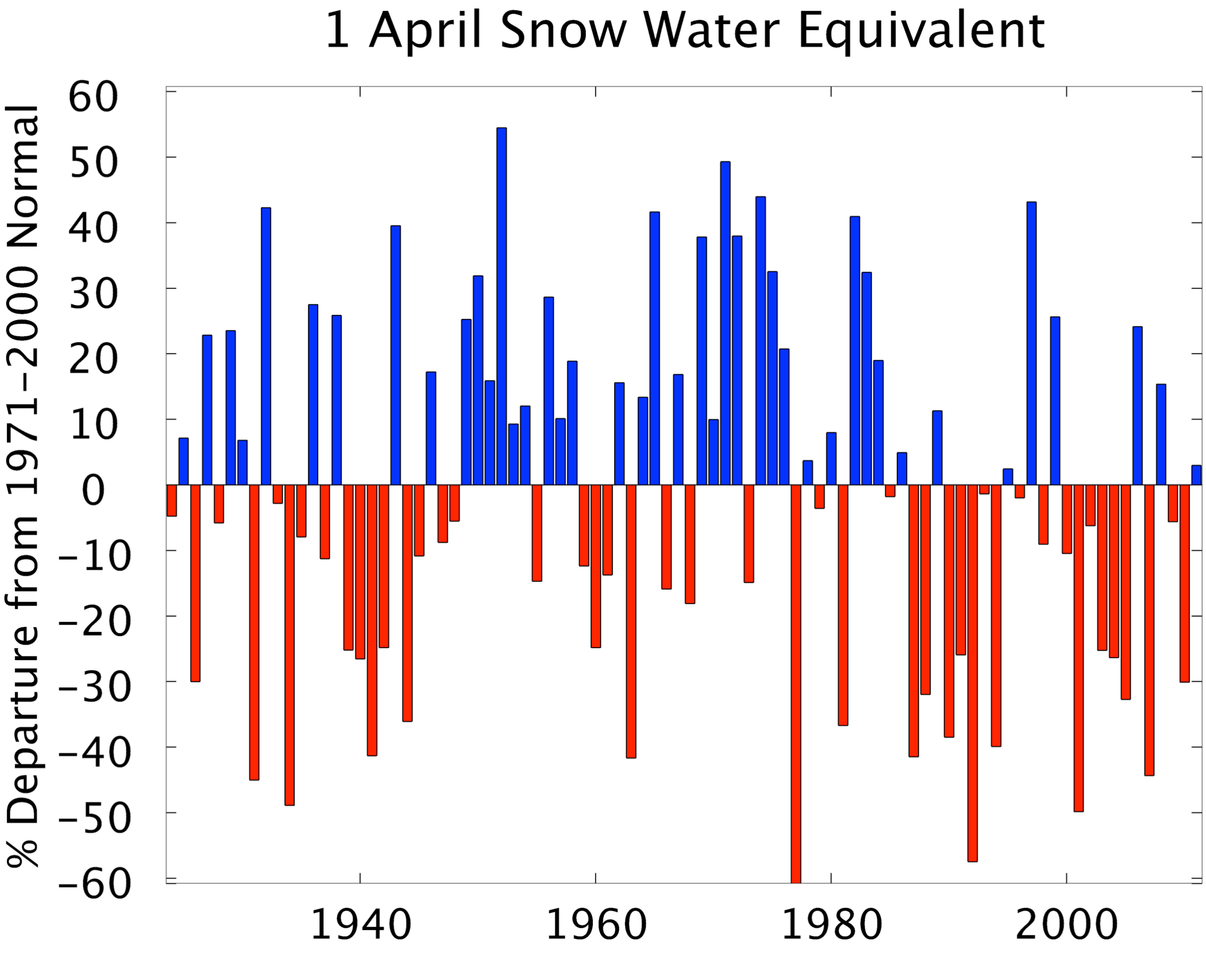


Figure 2.7. Snowpack indicator: April 1st snow water equivalent for each year relative to the mean of 1971-2000 (normal) for 126 sites in Idaho, USA (see Fig. 4 for locations).

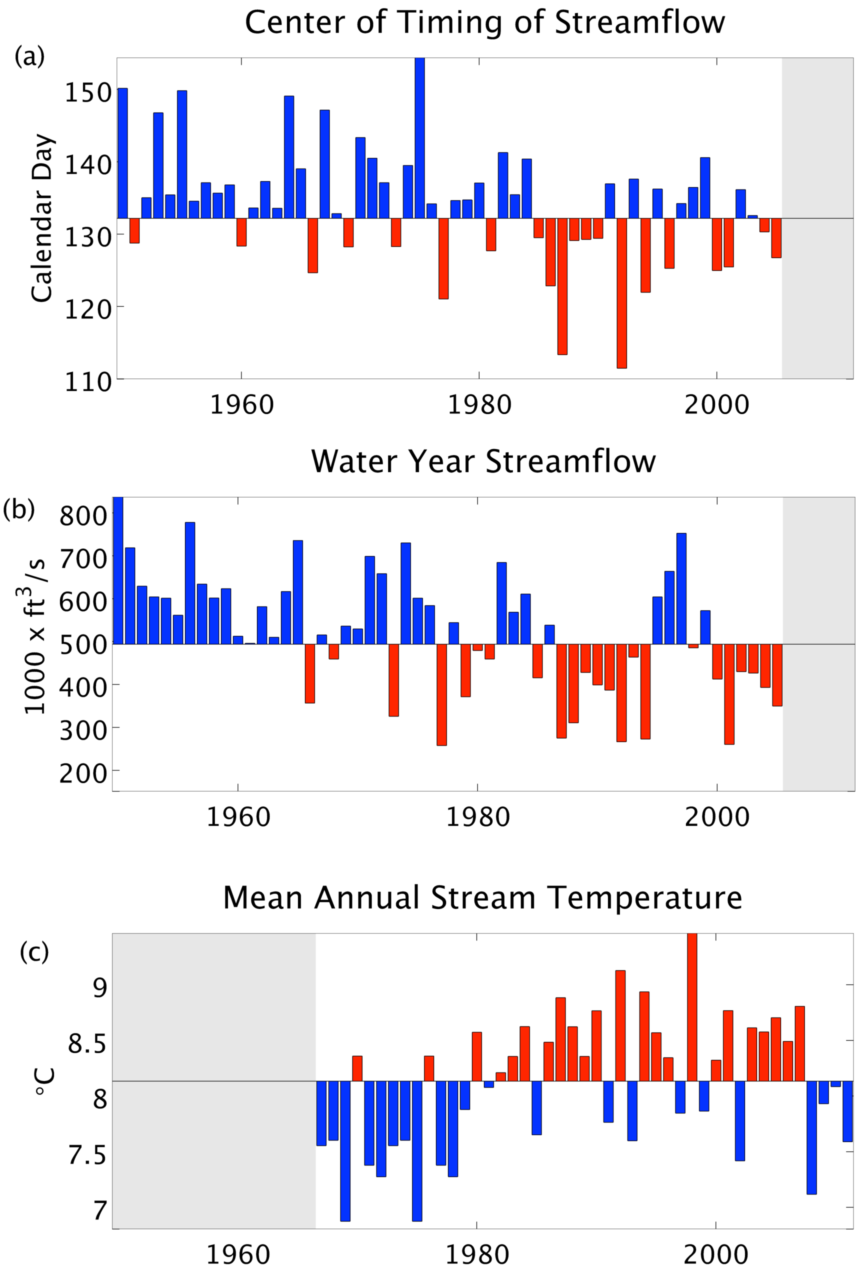
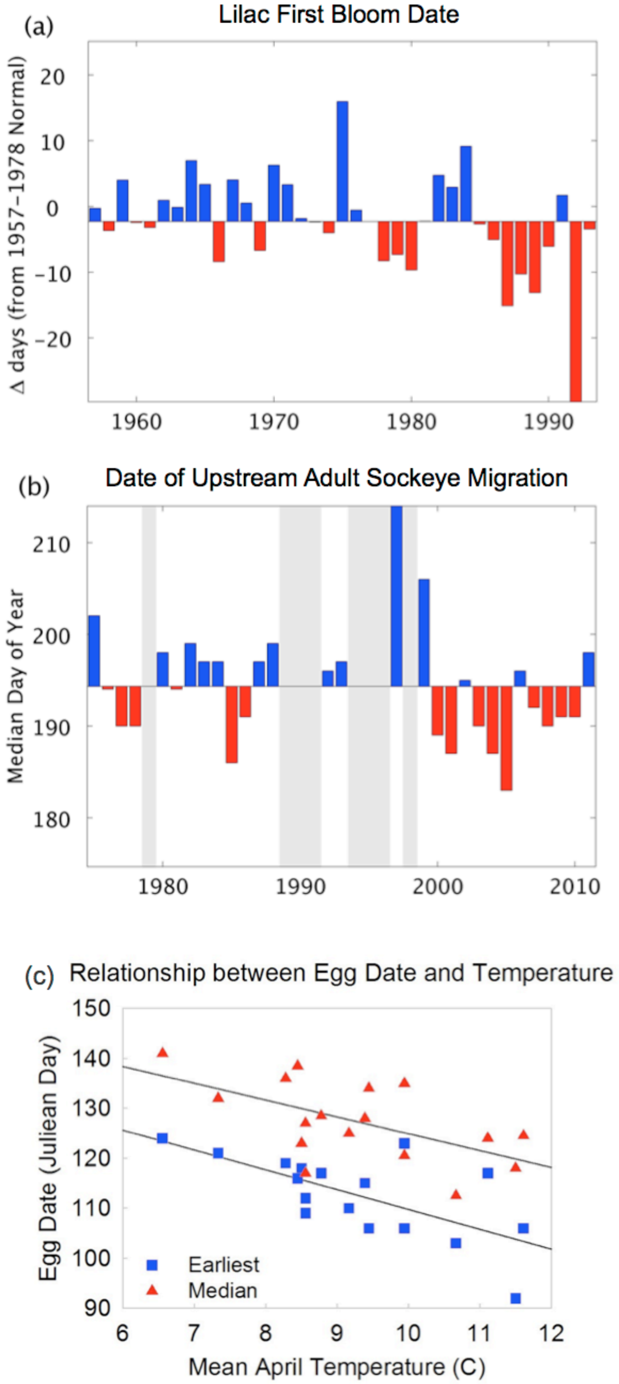


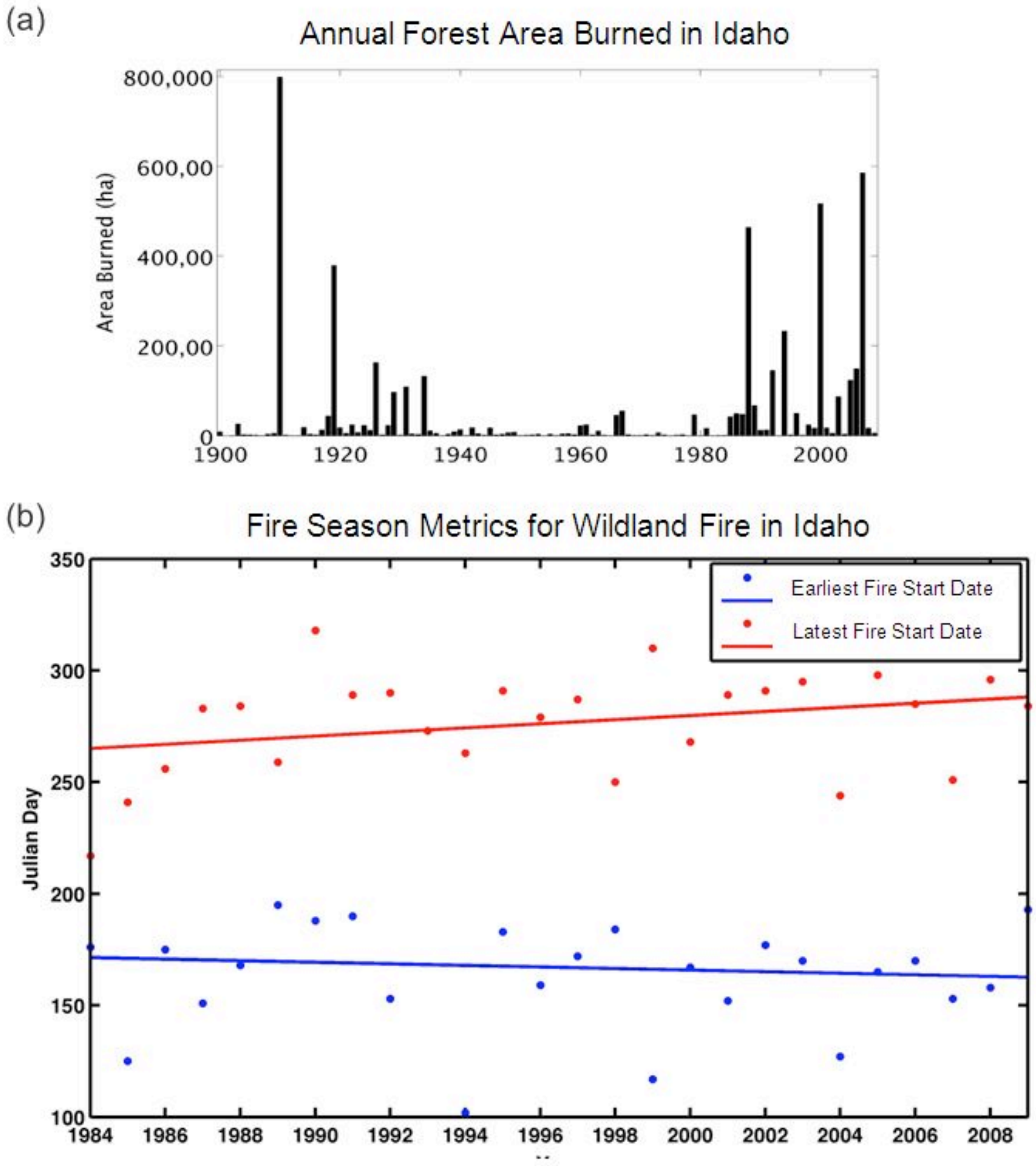
Figure 2.8. Hydrologic indicators: **8a**) Mean day of calendar year for center of timing of streamflow across 26 stations in Idaho, USA, **8b**) Mean water-year volumetric flow in a thousand cubic feet per second across the same 26 stations, and **8c**) Annual mean stream temperature for the North Fork Clearwater River, north-central Idaho, USA. See Fig. 4 for station locations.


(a) Lilac First Bloom Date

(b) Date of Upstream Adult Sockeye Migration

(c) Relationship between Egg Date and Temperature

Figure 2.9. Phenology indicators: **9a**) Mean statewide (variable number of sites) day of year for first bloom of lilac relative to the average 1957-1978 normal (mean of the analysis period), **9b**) Median date of upstream adult sockeye salmon migration as recorded (gray = missing data) at Lower Granite Dam, the uppermost dam on the lower Snake River near the Washington/Idaho border, USA and **9c**) Linear regression of mountain bluebird earliest and median egg date as a function of mean April temperatures; data (*n* = 17) are from locations near Arrowrock Dam, Elmore County, Idaho, USA from 1992–2006, 2009, and 2011.


(a) Annual Forest Area Burned in Idaho

(b) Fire Season Metrics for Wildland Fire in Idaho

Figure 2.10. Wildland fire indicators: **10a**) Annual area burned by wildland fire in Idaho forests (updated from Morgan et al. 2008), and **10b**) Fire season metrics for all wildland fires greater than 400 ha in Idaho, USA; fire season length is defined as the difference between the earliest fire start date (blue) and the latest fire start date (red) within a single year.

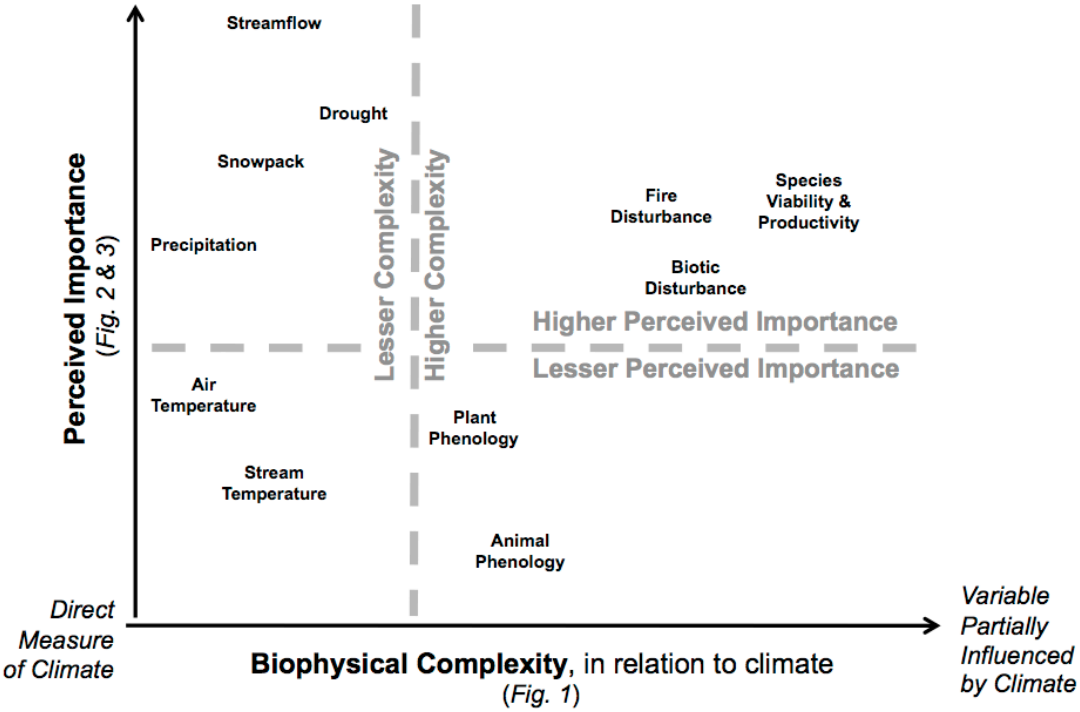


Figure 2.11. Conceptual model useful when considering which climate change indicators to focus research and/or outreach efforts upon for local-to-regional scale assessments. Levels of biophysical complexity and perceived importance are qualitatively derived from differences highlighted in Figure 1 and Figures 2 & 3, respectively.

CHAPTER 3

Extent of the rain-snow transition zone in the western U.S. under historic and projected climate

P. Zion Klos, Timothy E. Link, John T. Abatzoglou

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Abstract

This study investigates the extent of the rain-snow transition zone across the complex terrain of the western United States for both late 20th century climate and projected changes in climate by the mid-21st century. Observed and projected temperature and precipitation data at 4 km-resolution were used with an empirical probabilistic precipitation phase model to estimate and map the likelihood of snow versus rain occurrence. This approach identifies areas most likely to undergo precipitation phase change over the next half century. At broad scales, these projections indicate an average 30 percent decrease in areal extent of winter wet-day temperatures conducive to snowfall over the western United States. At higher resolution scales, this approach identifies existing and potential experimental sites best suited for research investigating the mechanisms linking precipitation phase change to a broad array of

processes, such as shifts in rain-on-snow flood risk, timing of water resource availability, and ecosystem dynamics.

Introduction

The western United States (U.S.) is strongly dependent on wintertime precipitation phase and snowpack accumulation to sustain a multitude of ecosystem goods and services [*Magoun and Copeland*, 1998; *Barnett et al.*, 2005; *Bales et al.*, 2006]. Assessment of the region's sensitivity of water resource availability to climate change is confounded by complex terrain and large heterogeneity in temperature and precipitation projections [*Elsner et al.,* 2010]. A detailed spatial assessment of these projected changes is particularly important in the climatic rain-snow transition zone, defined here as the transition between wintertime precipitation regimes that are strongly (near 100% climatically) rain- and snow- dominated. These areas are in the process of undergoing a major hydrologic shift as the phase of wintertime precipitation changes from predominantly snow to rain [*Knowles et al.*, 2006; *Abatzoglou*, 2011]. Observations support changes in hydrologic indicators dependent on precipitation phase, including: widespread decreased spring snowpack [*Mote et al.*, 2005; *Mote*, 2006; *Bales et al.*, 2006; *Knowles et al.*, 2006; *Pederson et al.*, 2011; *Kapnick and Hall*, 2012], increased rain-on-snow flood risk [*McCabe et al.*, 2007], and earlier snowmelt-driven streamflows in mountain catchments [*Cayan et al.*, 2001; *Barnett et al.*, 2005; *Regonda et al.*, 2005; *Bales et al.*, 2006; *Luce and Holden,* 2009*; Nayak et al.,* 2010; *Fritze et al.,* 2011].

The present location of the climatic rain-snow transition zone has been identified in several locales based on relatively long-term climatic observations [e.g. *Nayak et al.*, 2010; *Hunsaker et al.*, 2012; *Minder and Kingsmill*, 2013]. Maps of 'at-risk' snowpack at the 4 km scale have been created for the maritime snow region in the U. S. Pacific Northwest [*Nolin* *and Daly*, 2006], for potential late season snowpack changes in the western U.S. at 0.5 km scale [*McKelvey et al.*, 2011], and at hemispheric to global scales at coarse and static temporal (e.g. annual mean) and spatial (e.g. 200 to 50 km) resolutions [*Sturm et al.*, 1995; *Barnett et al.*, 2005; *Kapnick and Delworth*, 2013; *Krasting et al.*, 2013]. Assessment of the sensitivity of snow-dominated landscapes to projected future temperatures at finer spatial and temporal resolutions is needed to develop climate change adaptation strategies, particularly within the highly heterogeneous complex terrain of the western U.S.

The primary objective of this study is to estimate the location of the climatic rain-snow transition zone based specifically on temperatures from days with appreciable precipitation accumulation. We also pair observed and projected changes in wet-day temperature at high spatial resolution to better aid the research and management communities to evaluate where, when, and how hydrologic impacts of rain-snow changes are likely to occur throughout the western U.S. Finally, the study summarizes changes within different sub-regions of the western U.S. and highlights existing and potential experimental sites ideal for investigations that explore the mechanisms linking precipitation phase changes to a wide array of other coupled processes, including the timing of water resource availability, the risk of rain-on-snow flooding, and ecosystem dynamics.

Methods

The historic rain-snow transition zone was estimated using daily temperatures for wet days (precipitation >5 mm) using a 4-km horizontal resolution surface meteorology dataset [*Abatzoglou*, 2013] developed using data from NASA's Land Data Assimilation Systems (Phase 2) and the Parameter-elevation Relationships on Independent Slopes Model (PRISM [*Daly et al.,* 2008]) over the period 1979-2012. Grid elements that received fewer than 30 wet-days total within the 34-year combined record for each month (i.e. <30 out of approximately 1020 days) were excluded from analysis as they contribute little to precipitation-derived water resources. Monthly averaged wet-day temperatures were transformed using an empirically derived hyperbolic tangent function [*Dai*, 2008] to estimate the precipitation phase probability. The Dai [2008] equation was based on worldwide temperature-precipitation phase relationships from land-based stations. The function is bounded approximately by -2° and +4° C, where the phase probability ranges from 100% snow to 100% rain. We created precipitation phase-probability maps for individual months and for a mid-winter average of December - February wet-day temperatures.

Projected changes in wet-day temperatures were calculated using daily output of temperature and precipitation downscaled for 20 CMIP5 models for the late 20th (late20C, 1979-2012) and mid-21st century (mid21C, 2036-2065) to the aforementioned 4-km resolution grid using the Multivariate Adaptive Constructed Analogues method [*Abatzoglou and Brown*, 2012]. We constrain our projections to a single emissions scenario, RCP 8.5, given that inter-model variability generally exceeds scenario uncertainty for the first half of the 21st century [*Hawkins and Sutton*, 2009]. We calculated the average change in monthly and DJF wet-day temperatures across the 20 CMIP5 models, as the multi-model mean better isolates the signal of forced change and is often regarded as being more credible than any individual model [*Riechler and Kim*, 2008]. Projected changes in the multi-model mean wet-day temperature varied both by month and spatially, but generally showed a 1.5° to 4° C warming across the western U.S. by the 2036-2065 period. A delta-change procedure [e.g., *Wilby and Wigley*, 1997] was applied by adding historic monthly wet-day temperature from observations to projected changes in monthly wet-day temperature.

To quantify changes in precipitation phase across the entire western U.S., we aggregated the monthly wet-day snow-likelihood probabilities across the study area to calculate the proportion of land area receiving snowfall under both the historical and projected wet-day temperature regimes. We also performed an analysis using an overlay of both U.S. EPA Level-III Ecoregions and USGS HUC-4 Watersheds to assess changes in wintertime (mean DJF) phase regime at finer ecologically- and hydrologically-relevant scales across the region.

Results

Monthly maps (Figure 1) based on observed temperatures reveal strongly snow-dominated (100% snow-phase likelihood) precipitation in December - February (DJF) for the mountains of the western U.S., particularly the high Rocky Mountains, Cascades, and Sierra Nevada (Figure 1). The shoulder months of November and March exhibit similar spatial patterns, but with less spatially contiguous probability of snowfall relative to DJF. April qualitatively exhibits the highest spatial variability in phase distributions across the landscape, with a strong contrast in the likelihood of rain versus snow between lower and higher elevations as the rain-snow transition zone moves upslope over the spring.

The projected rain-snow zones for the mid21C period (Figure 1) show continued snow-dominance for DJF across western mountains, particularly in the high Rocky Mountains and Sierra Nevada. Large areas, particularly many that were previously strongly snow-dominated in March and April in late20C, will likely begin to experience increased frequency of rainfall during these months. Furthermore, results suggest that many mountainous areas will be characterized by a mixed rain-snow regime in November, in contrast to the historic strongly snow-dominated precipitation regime. Exceptions to these changes are the mid-continental, higher elevation regions including the western portions of Wyoming, the greater Yellowstone ecoregion, the Uinta and Bighorn Ranges, mountains of east-central Idaho, central Colorado Rockies, and the high Sierra Nevada which remain relatively snow-dominated in November (Figure 1). Although DJF are still strongly snow-dominated in mid21C projections, there is a reduction in the total months of snow-conducive temperatures overall with the likelihood of rain increasing in the autumn (October, November) and spring (March, April, May) months.

Figure 2 depicts the historic rain-snow transition zone derived from the mean wet-day temperatures across the winter months (DJF), during which greater than 45 percent of the land area is strongly snow-dominated in the western U.S. (Figure 3). The actual extent of areas dominated by rain and snow are variable over time and change throughout the winter, however this aggregated DJF calculation provides a means to estimate the areas that are generally characterized by winter precipitation in the form of rain versus snow during the historic late20C period. The difference in average wintertime strongly snow-dominated extent between the late20C and mid21C time periods is shaded light gray to highlight the areas that this analysis indicates are likely to shift from strongly snow-dominated (100% snow likelihood) to a rain-snow mix (<100% snow likelihood).

Figure 3 quantifies the extent of change in snow-dominance across the western U.S. When comparing the historic to the mid21C October through April periods, all show reductions in the percent of land area within a snowfall-conducive temperature regime across the western U.S. December through February show the largest reductions, ranging from a 26 to 32 percent decrease in total land area containing a snowfall-conducive temperature regime. For a conceptual comparison, by mid-century it is predicted that the strongly snow-dominated portions of the western U.S. will decrease by ~2 months in length, with the mid21C spatial patterns for December, January, and February qualitatively similar to the late20C patterns of November and March (Figure 1, Figure 3).

Table 1 showcases the changes in areal extent between late20C and mid21C for mean DJF strongly snow-dominated and strongly rain-dominated (100% rain-phase likelihood) areas across all the EPA Level-III ecoregions and HUC-4 watersheds that comprise the western U.S. Table 1 ranks these quantified changes by the proportion of loss (by mid 21C) in the percent of late20C strongly snow-dominated area, with areas projected to see 100%-loss of their strongly snow-dominated area at the top of the list. Within the ecoregions, mountain ranges of the northwestern U.S. (e.g. Northern Rockies, North Cascades, Blue Mountains) display 100%-loss of strongly snow-dominated area by late20C, and the highest percent of total internal area lost (56%, 48%, 27% respectively) within this 100%-loss grouping. The findings indicate that portions of many western ecoregions are likely to undergo a fundamental change in mid-winter hydrologic regime with rain events projected to be more common in areas where historically they were relatively rare. Some ecoregions display only small proportional area moving out of the strongly snow-dominated phase regime, but do display large increases in the proportional area of the strongly rain-dominated phase regime, demonstrating that much of the area within these regions is projected to move out of the climatic DJF rain-snow transition zone by mid21C (e.g. Colorado Plateaus, Central Basin and Range, Columbia Plateau).

For the analysis of regional watersheds (HUC-4), 100%-loss of strongly snow-dominated area occurs mainly in basins with moderate relief and elevation, (e.g. Middle Snake, Great Salt Lake, Oregon Closed Basins). Basins with greater relief however have higher late20C strongly snow-dominated areal extent, but are not projected to have a 100%-loss of strongly snow-dominated area because some limited areas at higher elevations are projected to stay within a strongly snow-dominated wintertime regime (e.g. Bear, White-Yampa, Upper Snake). Basins that comprise the highest elevation headwater regions are still projected to have large proportional losses in strongly snow-dominated area (all >38% loss) but also are projected to retain some of the largest strongly snow-dominated areal extents by mid21C (e.g. Upper Yellowstone, Rio Grande Headwaters, Colorado Headwaters, Gunnison).

Discussion

Recent studies across the western U. S. have highlighted research sites within the context of either being rain-dominated, snow-dominated, or transitional rain-snow climate. Qualitatively our findings are supported by analyses of empirical data from the Southern Sierra Critical Zone Observatory [*Hunsaker et al.*, 2012], Reynolds Creek Critical Zone Observatory [*Nayak et al.*, 2010], H.J. Andrews Experimental Forest [*Jones and Perkins*, 2010], and Mica Creek Experimental Watershed [*Hubbart et al.*, 2007], all of which are located within or near the rain-snow transition zone (Figure 2). Quantitatively, the accuracy of these findings is controlled directly by the phase/temperature relationships derived from global land-based observational datasets [*Dai*, 2008], which may differ slightly from regional phase/temperature relationships unique to specific locales in the western U.S. Additionally, the empirical Dai [2008] precipitation phase relationships are based on seasonal means calculated for each annual quarter and are derived from 3-hourly precipitation phase observations. This is somewhat different than the daily-scale temperature analysis (with aggregation to monthly and seasonal time-steps) used for wet-day phase calculations within this study. The accuracy of the findings could be enhanced through additional work with improved empirical relationships to estimate the phase likelihood; for example, by including variables such as vapor pressure, as has been done at more localized scales when sufficient data are available [*Marks et al., 2013*]. Furthermore, additional improvements within high-resolution spatially continuous datasets of surface meteorological variables would provide increased accuracy for the driving interpolated climate data, particularly in regions of the western U.S. where data in complex terrain are especially sparse and limit the PRISM methodology, leading to increased localized error [*Daly et al.*, 2009]. Despite these nuances, this analysis should effectively capture the general spatiotemporal trends of transitioning precipitation phase regime across the western U.S.

Implications for timing of peak snow-water equivalent (SWE)

Mountainous regions in the western U.S. have historically been strongly snow-dominated from November through March. The sensitivity analysis revealed that by mid21C the length of snowfall-conducive temperatures over many western mountain ranges will be reduced from approximately five (November - March) to approximately three (DJF) months of the year (Figures 1 and 3). Considering these temporal changes, it will be critical for the water resources research and management communities to look beyond the April 1 standard for measurement of approximate peak SWE [*Pederson et al.*, 2011]. The idea that a standard protocol, such as a fixed date, can be continually valid has been challenged previously when considering water resources and climate change [*Milly et al.*, 2008]. Other studies have stated a similar need to change the time of peak SWE evaluation in an effort to better predict resulting springtime high flows and aid water managers [*Hunsaker et al.*, 2012; *Meromy et al.*, 2013].

Although this April 1 standard is used widely in current practice for evaluating snowpack, spatially explicit evaluation dates, which are unique to the changing precipitation regimes of different western U.S. mountain ranges, may be more appropriate. A spatially-explicit evaluation may be particularly important in areas where the majority of snowfall historically occurred within the spring window of March, April, and May (common for many regions closer to the continental interior). Regions historically dependent on large snowfall amounts in these spring months may be more sensitive to the impacts of changing climate on snowpack because although DJF remain cold enough to be strongly snow-dominated, large changes may still occur when spring temperatures approach the rain-snow threshold. Thus, as a response to this spatial complexity, and to advance the public and scientific understanding of regional- to local-scale effects of changing climate, this study provides high-resolution, spatial data products that allow for this spatially-explicit assessment of snowfall-conducive temperature regimes.

Regional considerations

In many areas, the rain-snow transition zone is broad because controlling horizontal temperature gradients are subtle, due primarily to a combination of location (elevation and latitude) and low topographic relief. In contrast, the transition zone is narrower in regions with steep elevational, and hence steep temperature gradients. These relationships suggest that many relatively large areas that contain lower relief, mid-elevation mountain ranges will likely shift relatively quickly into new precipitation phase regimes (e.g. the Northern Rockies, North Cascades, and Blue Mountains ecoregions, Table 1). Alternatively, areas with steeper elevational gradients will likely have a smaller portion of land area shift into, or exit the transition zone in the near future (e.g. the Sierra Nevada, Central Rockies, and Southern

Rockies ecoregions, Table 1). The interior northwestern U.S. shows a greater sensitivity of its strongly snow-dominated areas to warming because much of the region is characterized by relatively warm winter temperatures and by mainly mid-elevation mountain ranges. This is in accordance with empirical work that suggests that the timing of peak flows have advanced at a faster rate in the northwestern U.S., compared to other regions in the western U.S. [*Regonda et al.*, 2005]. Our findings highlight the spatial and temporal complexity of changes and indicate how certain experimental sites within the western U.S. are better positioned to help assess the impact of these changes on precipitation phase and associated ecohydrological processes (Figure 2).

Resources for the greater scientific research community

The locations of selected long-term research sites are included (Figure 2) to help the research community identify where these sites occur within the rain-snow transition zones, and where potential future sites are warranted to fill gaps within the existing monitoring and hydrologic research network. An inset of Yosemite National Park provides a detailed view that highlights the relatively fine resolution of the results across a steep elevational gradient (Figure 2). This high spatial resolution allows individual small watersheds, down to tens of km^2, to be characterized within the rain-snow transition zone, showing where a gradient of rain- or snow- dominated temperature regimes existed historically and where new wintertime rain-snow transitional temperature regimes are projected to exist by the mid21C. Similarly, tabulated results of the spatial analysis (Table 1) allow the research and planning community to compare and estimate projected changes relevant to more localized questions focused within specific watersheds and/or ecoregions.

Conclusions

As demonstrated through the mapped temperature-precipitation phase relationship across the western U.S., the climatic rain-snow transition zone will move up in altitude and latitude. The western U.S. is projected to see an average monthly reduction from ~53% to ~24% in the extent of the land area within a wintertime snowfall regime (Figure 3). The climatic mean annual duration of the snowfall regime will also be reduced across the western U.S. with the annual duration of 100% snow-dominated precipitation decreasing by mid21C from approximately five to approximately three (DJF) months of the year on average for many of the western mountain ranges (Figure 1, Figure 3). Findings demonstrate that changes in the climatic extent will be complex and that many established research sites are, or will be, better poised than others to conduct research advancing the understanding of how these shifts in precipitation phase at a climatic scale may impact integrated hydrologic, ecologic, and social systems. As a resource for the research and planning communities, full-resolution maps and datasets of historic and projected rain-, transitional-, and snow- dominated extent at monthly and integrated DJF time intervals are available for public download through the corresponding author's website.

Acknowledgements

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Tables

Table 3.1. Changes in Wintertime Precipitation Phase by Region

Region	Strongly snow-dominated extent in late20C (%)	Change in strongly snow-dominated extent by mid21C (%)	Strongly rain-dominated extent in late20C (%)	Change in strongly rain-dominated extent by mid21C (%)
US EPA Level-III Ecoregions				
15 NORTHERN ROCKIES	56	-56	0	+3
77 NORTH CASCADES	48	-48	1	+18
11 BLUE MOUNTAINS	27	-27	0	+29
80 NORTHERN BASIN AND RANGE	18	-18	0	+23
20 COLORADO PLATEAUS	18	-18	6	+50
04 CASCADES	6	-6	17	+42
13 CENTRAL BASIN AND RANGE	6	-6	2	+66
09 EASTERN CASCADES SLOPES AND FOOTHILLS	5	-5	0	+27
10 COLUMBIA PLATEAU	3	-3	0	+65
23 ARIZONA/NEW MEXICO MOUNTAINS	1	-1	36	+54
12 SNAKE RIVER PLAIN	44	-42	0	+29
16 IDAHO BATHOLITH	88	-79	0	+1
19 WASATCH AND UINTA MOUNTAINS	68	-60	0	+8
18 WYOMING BASIN	44	-37	0	0
05 SIERRA NEVADA	19	-14	26	+26
41 CANADIAN ROCKIES	100	-67	0	0
22 ARIZONA/NEW MEXICO PLATEAU	3	-2	20	+71
17 MIDDLE ROCKIES	82	-46	0	0
21 SOUTHERN ROCKIES	69	-34	0	+3
08 SOUTHERN CALIFORNIA MOUNTAINS	0	0	77	+16
14 MOJAVE BASIN AND RANGE	0	0	95	+4
01 COAST RANGE	0	0	88	+11
02 PUGET LOWLAND	0	0	95	+5
03 WILLAMETTE VALLEY	0	0	99	+1
06 SOUTHERN AND CENTRAL CALIFORNIA CHAPARRAL AND OAK WOODLANDS	0	0	99	+1
07 CENTRAL CALIFORNIA VALLEY	0	0	100	0
78 KLAMATH MOUNTAINS	0	0	65	+30
79 MADREAN ARCHIPELAGO	0	0	99	+1

81 SONORAN BASIN AND RANGE	0	0	100	0
USGS HUC-4 Watersheds				
MIDDLE SNAKE	29	-29	0	+23
GREAT SALT LAKE	16	-16	0	+56
YAKIMA	16	-16	0	+25
ESCALANTE DESERT SEVIER LAKE	14	-14	0	+70
BLACK ROCK DESERT HUMBOLDT	14	-14	0	+49
OREGON CLOSED BASINS	13	-13	0	+26
UPPER COLORADO DIRTY DEVIL	12	-12	10	+64
PUGET SOUND	7	-7	40	+18
MIDDLE COLUMBIA	6	-6	0	+54
CENTRAL LAHONTAN	5	-5	1	+75
UPPER CANADIAN	4	-4	30	+18
CENTRAL NEVADA DESERT BASINS	4	-4	11	+53
SALT	1	-1	59	+31
SACRAMENTO	1	-1	54	+26
LOWER COLORADO LAKE MEAD	1	-1	59	+35
NORTH LAHONTAN	1	-1	0	+50
KLAMATH NORTHERN CALIFORNIA COASTAL	1	-1	46	+27
WILLAMETTE	1	-1	64	+25
UPPER PECOS	1	-1	71	+23
BEAR	79	-76	0	+3
RIO GRANDE ELEPHANT BUTTE	12	-11	22	+51
UPPER COLORADO DOLORES	17	-15	0	+54
LOWER SNAKE	50	-44	0	+25
LOWER GREEN	55	-48	0	+15
WHITE YAMPA	81	-69	0	0
POWDER TONGUE	36	-29	0	0
SAN JOAQUIN	10	-8	74	+8
MISSOURI MUSSELSHELL	35	-27	0	0
MISSOURI MARIAS	44	-33	0	0
UPPER SNAKE	74	-55	0	+8
LOWER YELLOWSTONE	24	-17	0	0
SAN JUAN	10	-7	1	+77
LOWER COLUMBIA	3	-2	45	+34
NORTHERN MOJAVE MONO LAKE	3	-2	79	+11
MISSOURI HEADWATERS	69	-44	0	0
TULARE BUENA VISTA LAKES	10	-6	76	+7
GREAT DIVIDE UPPER GREEN	52	-31	0	0
BIG HORN	40	-23	0	0
UPPER YELLOWSTONE	62	-32	0	0
RIO GRANDE HEADWATERS	65	-29	0	0

COLORADO HEADWATERS	73	-30	0	+11
GUNNISON	68	-26	0	+13
OREGON WASHINGTON COASTAL	0	0	79	+15
LITTLE COLORADO	0	0	13	+83
SOUTHERN CALIFORNIA COASTAL	0	0	85	+3
SOUTHERN MOJAVE SALTON SEA	0	0	95	+1
CENTRAL CALIFORNIA COASTAL	0	0	97	+1
LOWER COLORADO	0	0	82	+3
LOWER GILA	0	0	99	+1
MIDDLE GILA	0	0	96	+1
SAN FRANCISCO BAY	0	0	98	0
UPPER GILA	0	0	72	+27

[a] Based on mean strongly snow- and rain-dominated areal extent for the winter months (DJF) between historic (late20C) and projected (mid21C) climate; ranked by greatest proportional loss by mid21C in the displayed percent of late20C strongly snow-dominated areal extent.

Figures

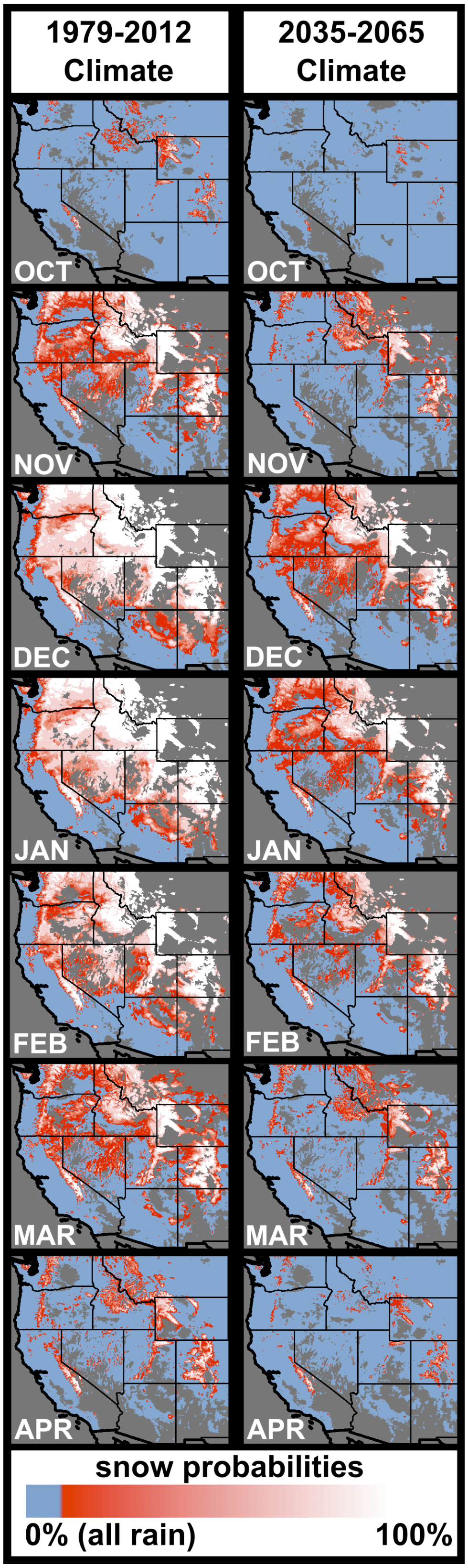

Figure 3.1. The current and future extent of the strongly rain-dominated (blue), strongly snow-dominated (white), and rain-snow mix (pink to red) areas within the western US based on wet-day mean temperature. Future extents are based upon the RCP8.5 scenario using a 20-model GCM mean. (ΔT ranging from ~1.5 to ~4 °C spatially).

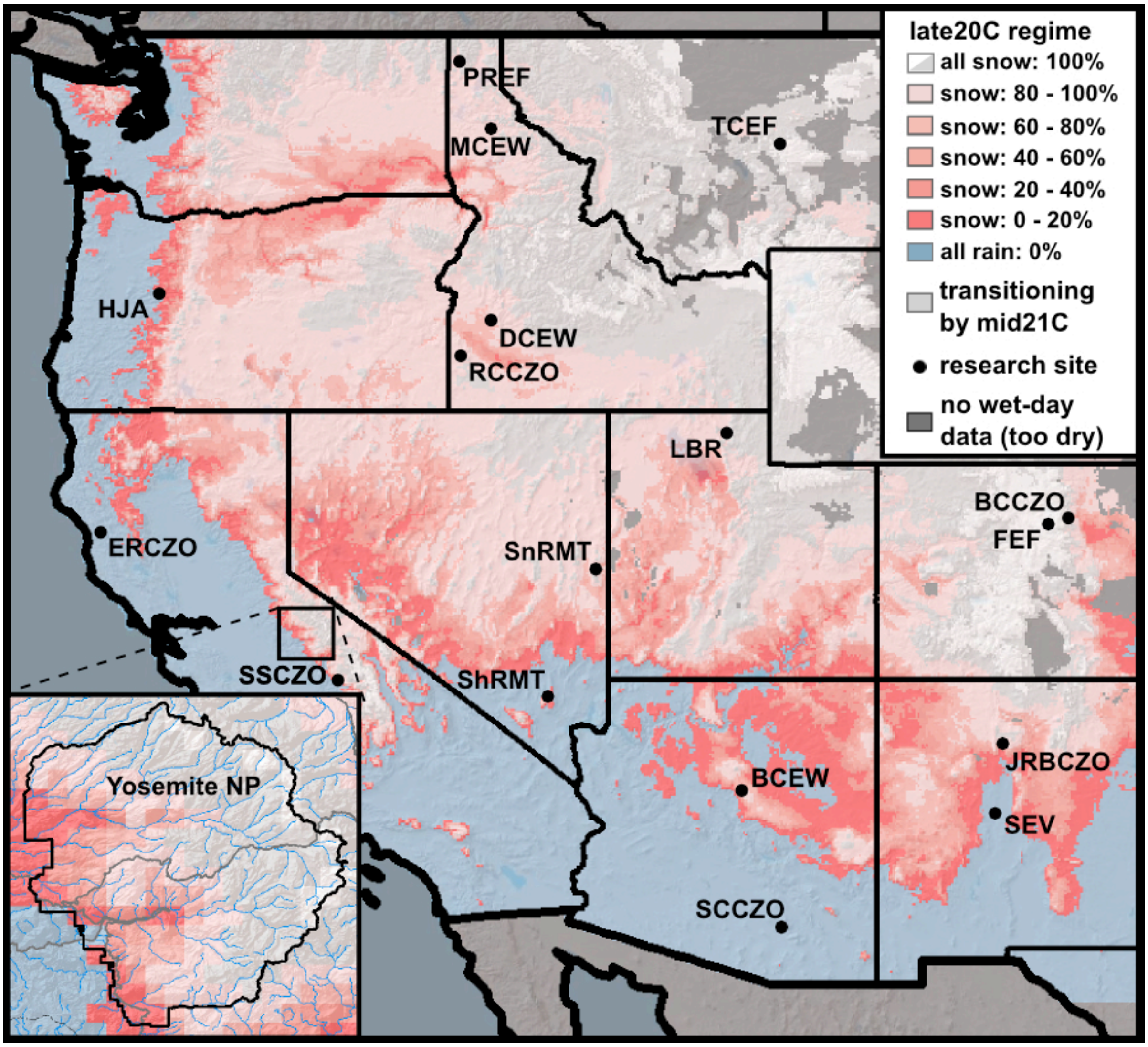

Figure 3.2. Current extent of strongly snow-dominated (white), strongly rain-dominated (blue), and mixed phase (pink to red) precipitation regimes based on the mean wet-day winter temperature (1979-2012 Climate Period, DJF_{mean}) and the encroachment (light gray) of the mixed-phase rain-snow transition zone into previously 100% snow-dominated areas. Inset of Yosemite National Park to display spatial resolution. Locations of selected experimental sites include: Boulder Creek Critical Zone Observatory (BCCZO), Beaver Creek Experimental Watershed (BCEW), Dry Creek E. W. (DCEW), Fraser Experimental Forest (FEF), H. J. Andrews E. F. (HJA), Jemez River Basin C. Z. O. (JRBCZO), Little Bear River WATERS testbed (LBR), Mica Creek E. W. (MCEW), Priest River E. F. (PREF), Reynolds Creek E. W., C. Z. O., and WATERS testbed (RCEW), Santa Catalina C. Z. O. (SCCZO), Sevilleta Research Site (SEV), Sheep Range Meteorological Transect (ShRMT), Snake Range M. T. (SnRMT), Southern Sierra C. Z. O. (SSCZO), Tenderfoot Creek E. F. (TCEF).

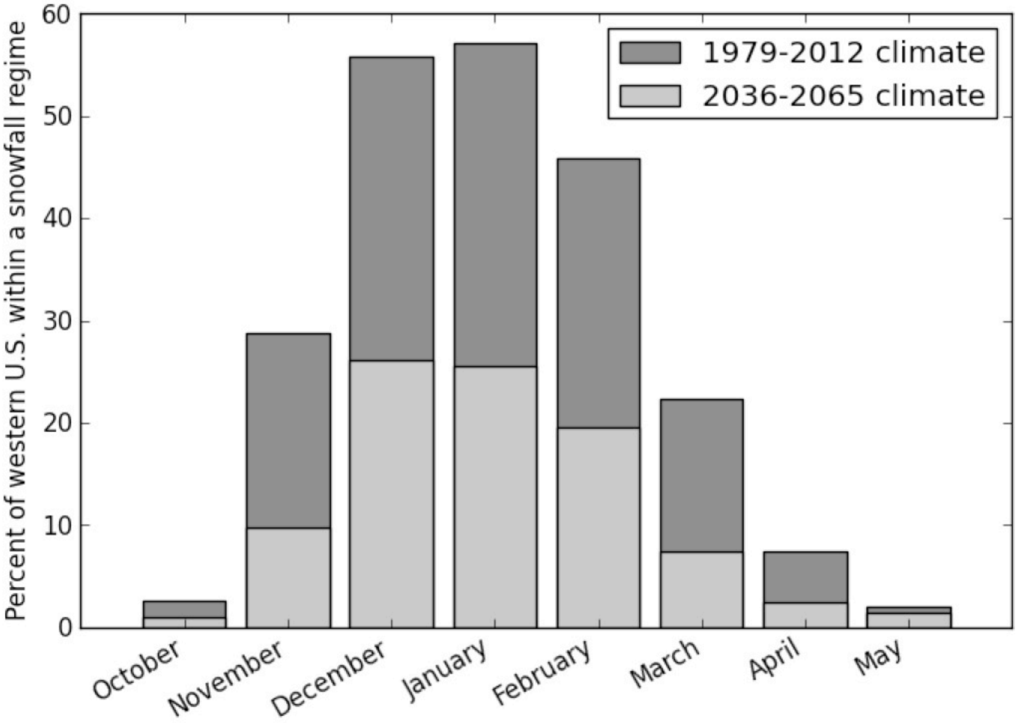

Figure 3.3. A quantitative summary of historical and projected areal extent of snowfall-conducive temperatures across the entire western U.S. (west of -100° longitude). Future extents are based upon the RCP8.5 scenario using a 20-model GCM mean. (ΔT ranging from ~1.5 to ~4 °C spatially).

CHAPTER 4

Managing for climate change on federal lands of the Western U.S.: Perceived usefulness of climate science, effectiveness of adaptation strategies, and barriers to implementation

Kerry B. Kemp, Jarod J. Blades, P. Zion Klos, Troy E. Hall, Jo Ellen Force, Penelope Morgan, Wade T. Tinkham

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Abstract

Recent mandates in the United States require federal agencies to incorporate climate change science into land management planning efforts. These mandates target possible adaptation and mitigation strategies. Yet, the degree to which climate change is actively being considered in agency planning and management decisions is largely unknown. We explored the usefulness of climate change science for federal resource managers, focusing on the efficacy of potential adaptation strategies and barriers limiting the use of climate change science in adaptation efforts. Our study was conducted in the northern Rocky Mountains region of the western U.S., where we interacted with 77 U.S. Forest Service and Bureau of

Land Management personnel through surveys, semi-structured interviews, and four collaborative workshops at locations across Idaho and Montana. We used a mixed-methods approach to evaluate managers' perceptions about adapting to and mitigating for climate change. Although resource managers incorporate general language about climate change in regional and landscape-level planning documents, they are currently not planning on-the-ground adaptation or mitigation projects. However, managers felt that their organizations were most likely to adapt to climate change through use of existing management strategies that are already widely implemented for other non-climate related management goals. These existing strategies (e.g., thinning, prescribed burning) are perceived as more feasible than new climate-specific methods (e.g., assisted migration) because they already have public and agency support, accomplish multiple goals, and require less anticipation of the future timing and probability of climate change impacts. Participants reported that the most common barriers for using climate change information included a lack of management-relevant climate change science, inconsistent agency guidance, and time and resources needed to access, interpret, and apply current climate science information to management plans.

Introduction

In the U.S. northern Rocky Mountain region, the United States Forest Service (USFS) and Bureau of Land Management (BLM) are responsible for managing public lands that account for roughly 13 million hectares in Idaho and 11 million hectares in Montana (Gorte et al. 2012). Climate change is likely to impact the forests and rangelands managed by these agencies and alter important ecosystem services, such as fresh drinking water sources, recreation, and timber production, all of which are integral to local communities and economies (e.g., Pederson et al. 2006). Therefore, how these agencies adjust their current management practices to adapt to and mitigate the impacts of climate change will be an important aspect of future land management.

Federal agencies have emphasized climate change within planning and management at the national level for several years. In 2008, the USFS acknowledged the role climate change has played in changing wildfire regimes, bark beetle infestations, and water availability, stating that, "Without fully integrating consideration of climate change impacts into planning and actions, the Forest Service can no longer fulfill its mission" (Dillard et al. 2008, pg. 2). The USFS highlighted two strategies for addressing climate change impacts on national forests: facilitated adaptation, i.e., actions for reducing the negative impacts of climate change; and mitigation, i.e., actions to reduce emissions and enhance natural carbon sequestration (Dillard et al. 2008, Cruce and Holsinger 2010). Additionally, the USFS created the "Climate Change Performance Scorecard," which was intended to help units within the agency implement "short-term initiatives" and "long-term investments" in response to projected impacts of climate change, as well as track their progress towards these goals (Tkacz et al. 2010). Likewise, the BLM has had a strategy for responding to climate change in place since 2001, though potentially less targeted than the guidance put forth by the USFS (Ellenwood et al. 2012). Furthermore, as part of Secretarial Order No. 3289, in 2009 the Department of the Interior (DOI) established several Climate Science Centers and Landscape Conservation Cooperatives to address informational concerns and anticipated challenges the DOI may face in managing for the impacts of climate change (GAO 2007). Presidential executive orders issued in 2009 (EO 13514) and 2013 (EO 13653) also provided uniform policy guidance aimed at encouraging climate change adaptation and carbon mitigation within all federal agencies.

Although federal mandates are in place, addressing climate change at regional (unit/forest/watershed) and local (field office/district/stand) levels presents numerous challenges, especially within impact assessments designed for long-term land use planning or specific management projects. These challenges include both internal and external factors, such as a lack of agency direction (Archie et al. 2012), time and funding allocated for implementing new programs, litigation by external interest groups (Lachapelle et al. 2003, Jantarasami et al. 2010, Wright 2010), or negative public perceptions (Archie et al. 2012, Archie 2013). Transferring science between research and management can also be a challenge. Managers often lack time to review relevant literature (Kocher et al. 2012) and a dearth of information at management-relevant scales can impede the use of existing science (Archie et al. 2012). For example, resource managers have repeatedly expressed a need for downscaled climate change projections to match the scales at which land management is accomplished (e.g., Jantarasami et al. 2010, Archie et al. 2012).

Climate change may also dictate that land managers consider novel approaches to land management to achieve their goals. Rangeland and forest management in the western U.S. often emphasizes evaluating current conditions against historical reference conditions and using the estimates of the degree of ecosystem change to prioritize different types of treatments (Keane et al. 2009, Caudle et al. 2013). The extent of change from past decades and centuries, coupled with predicted future changes, suggests that adaptive management approaches that consider a wide range of different options may be necessary to effectively carry out the provisions highlighted in agency policies for climate change (Hobbs et al. 2014).

Although climate change has been highlighted as an important management priority at the federal level, it is still uncertain how climate change science is being considered in project management and planning by local resource managers. Our research addresses how federal land management agencies in the U.S. northern Rocky Mountains are currently utilizing or thinking about applying climate change science to management activities. Specifically, we asked USFS and BLM managers how climate change science is useful for their work and whether they, as individuals, or their agencies are currently incorporating this information into land management planning. Additionally, we asked what management actions they see as effective for adapting to, or mitigating, climate change and if their agencies are considering implementation of these actions. Finally, if managers are not addressing climate change in their planning efforts as suggested by the policy directives, what barriers do they perceive impede their use and incorporation of it into management? Understanding the challenges resource managers perceive and the techniques they are using to adapt to the impacts of climate change will help to highlight the types of information, policies, and directives that can better aid managers in incorporating climate change science into management.

Methods

We used a series of different approaches, including quantitative surveys, semi-structured interviews, and one-day workshops, to understand managers' perceptions about the usefulness of climate change science, efficacy of potential adaptation strategies, and barriers to implementation of adaptation and mitigation measures. Survey and interview input was collected from study participants both before and after the workshops as part of a larger study to track individual changes in perceptions about climate change science (Blades 2013).

In this article, we aggregate individual responses from the surveys, interviews, and workshop discussions to focus on general tendencies and insights across participants, drawing on pre- and post-workshop responses that bear on our research questions where appropriate, rather than analyzing individual changes from pre- to post-workshop.

The vast majority (> 90%) of federal lands in Idaho and Montana are managed by the USFS and BLM, and these lands account for approximately 62 and 29%, respectively, of the land base of these two states (Gorte et al. 2012). Therefore, we elected to focus the majority of our recruitment efforts on these two agencies (USFS & BLM), though other federal (e.g., USFWS, NPS, NOAA), tribal, and state resource managers were invited to participate in our workshops. Participants who were likely to actively make or implement land management decisions, and whose agency experience would give them the ability to comment in depth on land management and climate change directives were purposively selected through public contact lists for the study. These participants were planners, ecologists and biologists, silviculturists, fire managers, and water resources managers. After the initial selection of participants, a snowball sampling approach was employed where individuals who agreed to participate were asked to identify other interested individuals or co-workers who would have knowledge of how agencies address climate change. We initially recruited 257 individuals to participate in the workshops, however; only 97 individuals elected to participate (38% response rate). Of those 97 individuals, 77 were federal land managers from the USFS (n = 66) and BLM (n = 11). All participants that signed up for the workshops were sent pre-workshop surveys, and a random sample of those responding to the surveys were asked for interviews. We elected to exclude individuals from other state and federal agencies because of the overall poor response rate from these agencies. We aggregated USFS and BLM responses for all phases of data collection based on the small representation by BLM employees. Both the USFS and BLM are mandated to manage for multiple uses and sustained-yields, and though these specific uses may differ slightly (e.g., timber harvest vs. cattle grazing and mining), many are similar (e.g., recreation, wildlife, water; Gorte et al. 2012). Likewise, both agencies must allow public participation in the planning process and address potential environmental impacts as part of the National Environmental Policy Act (NEPA) of 1969.

We conducted our one-day workshops in four locations across the northern Rocky Mountains in November 2012 (Figure 4.1). The locations represented five national forests and two BLM districts (Figure 4.1). Representatives of several collaborative organizations and non-profit groups who actively work with individuals from the USFS and BLM participated in the workshops, but here we focus specifically on federal resource managers' responses. During each 8-hr workshop, we presented historical information and future projections about climate change impacts at global, regional, and local scales. Most of the regional and local scale projections focused on changes in the northern Rocky Mountain region for resources of interest, including hydrology, forest species distributions, and wildfire activity. At the end of each presentation, workshop participants were assigned to small groups chosen to represent the mix of agencies, organizations, and specializations present. During these breakout discussions, participants were asked to reflect upon how climate change information could be useful in their work and important management implications of the information presented. Discussions were facilitated in a manner to provide all participants an opportunity to speak openly about their personal perceptions as well as to express opinions on behalf of their agencies. Main discussion points that arose during the conversations were recorded on flip-charts by trained facilitators.

Online surveys were sent to all workshop participants via e-mail prior to and immediately following the workshops. If participants had not completed an online survey prior to arriving at the workshop, they were asked to fill out a paper copy upon arrival. Quantitative survey responses were made on a 7-point Likert-type scale from -3 (strongly disagree) to + 3 (strongly agree) and descriptive statistics were summarized using SPSS version 13 (SPSS 2010). Where survey questions were asked both before and after the workshops, we present the results of only the pre-workshop data because we believe these data most closely reflect perceptions of the broader population of resource managers who have not participated in workshop presentations, discussions, or conversations. Several of the post-workshop survey questions explicitly asked participants about the perceived usefulness of information at varying spatial scales (global, regional, and local); we compare these ratings using one-way analysis of variance.

Pre-workshop interviews were conducted by phone in late October and early November, 2012. Questions during the pre-workshop interviews covered a range of topics related to perceptions of climate change and impacts, including credibility and salience of climate change science, perceived vulnerability to and severity of climate change impacts, and individual and collective management responses (Blades 2013). However, for the purposes of this analysis, we only included responses regarding the current use of climate change science, potential actions for adapting to and mitigating the effects of climate change, and barriers to using climate change science within management organizations. All interview questions were open-ended, allowing for a range of responses, and interviewers asked follow-up questions to clarify responses. Post-workshop interviews were conducted by phone in December 2012 and January 2013 and generally covered the same topics as the pre-workshop interviews, but also included evaluative components targeted to give the researchers feedback on the workshop materials and process (data not reported here; see Blades 2013).

Phone interviews were digitally recorded and transcribed. Following transcription, initial codes (high-level themes) were developed by one researcher and then evaluated by other members of the research team for clarity and completeness. The same codes were used for the pre- and post-workshop interviews and discussion group themes. After several initial rounds to refine the coding rules, all interviews and discussion points were coded using NVIVO 10.0 software (NVIVO 2012) by one researcher. A subset of interviews and discussion points was subsequently coded by a second researcher to establish reliability (kappa = 0.80; Krippendorff 2004). Sub-themes were subsequently developed under each high-level theme (code) using a peer-debriefing process where each researcher independently established important and cross-cutting points from the interviewees and the group summarized and corroborated common themes.

Results

We interviewed 60 individuals prior to participating in the workshops; 35 of those individuals were also interviewed after the workshop. In all, 77 resource managers participated in the four workshops, 61 of whom completed both the pre- and post-workshop online surveys. The responses we received from repeatedly engaging participants through different mediums allowed us to sufficiently understand managers' perceptions and to reach saturation of themes during the interviews and breakout discussions (Bowen 2008). In presenting results below, we integrate excerpts from interviews and workshop discussions chosen to exemplify the general themes we distilled from across the data sources we collected (Bansal and Corley 2012, Poortman and Schildkamp 2012).

Usefulness of climate change science

The majority of survey participants thought climate change science was useful for their work (90%), for future planning efforts (97%), or for specific management projects (80%; Figure 4.2). Furthermore, more than 80% of the land managers surveyed agreed or strongly agreed that using climate change science was within their job description or responsibilities (Figure 4.2), indicating an awareness of national policies aimed at adapting to and mitigating climate change. When asked in interviews and workshop discussions how climate change science is currently being used, many participants mentioned that it is addressed in environmental impact statements (EIS), environmental assessments (EA) and forest plans that have been recently revised, along with other disturbance factors (e.g., wildfire, bark beetles, floods). However, these documents often contain only broad, non-specific language. For example, one hydrologist mentioned that "cursory statements are put into our EISs or EAs, and it's more like checking a box than it is really looking into what… could be the potential effects [of climate change]."

During the workshop discussions, participants emphasized that climate change projections were useful for showing that adaptation may be necessary, but less useful in understanding how to adapt. This uncertainty about the best adaptation strategies meant that many of the resource managers we interviewed were unlikely to change their management practices to accommodate future change. For example, a timber manager from the Forest Service noted that he was not going to "change the species compositions when I prescribe a plant in a re-vegetation harvest area." Rather, he emphasized he would use the "stand dynamics [of] what has been there" to influence his "decision on what we're going to [plant in that stand] in the future." Likewise, managers found it difficult to understand how to incorporate climate change science into their planning efforts. For example, one planner noted that many of the Forest Service's management actions are still based on "our current understanding of climate being relatively static." This planner went on to emphasize that "We're not sure [of] the extent of climate change or what a 3°C increase in the global [mean temperature] means to us here locally. That's the problem, we know that there's a change globally, but what does that mean here on our 250,000 acres that we manage in northwest Montana? That has yet to be defined for us at a level we can [base] management decisions on." Like this individual, many other participants pointed out that "project level planning [takes place over] pretty short time periods (5-10 years)" and at the scale of hundreds of acres, requiring "very site-specific analysis," whereas climate change occurs over long periods and specific local impacts are difficult to predict. Thus, the current global and national-scale climate change projections are not very applicable for planning on-the-ground management activities.

Of the three spatial scales of information presented during the workshops (global, regional, and local), regional and local climate change projections were considered more useful for land management than global projections ($F_{3, 234} = 11.87$, $p << 0.001$; Table 4.1). However, interviews and workshop discussions revealed a more nuanced interpretation of the usefulness of different scales of information. Discussions during the workshop revealed that participants felt that "local-scale models lacked site-specific data" or that "there was too much variability" at this scale. One silviculturist felt that local-scale models had to consider "so many variables and so many complexities in the natural system" and that modeling those types of processes was "really hard." Workshop participants did comment that, conceptually, the scale of regional projections was useful for thinking about "potential consequences or priorities" and "desired future conditions" across the broader landscape.

Management to address the impacts of climate change

Participants were asked during the interviews and workshops if there were specific actions they felt would be useful for adapting to and mitigating the effects of climate change on federally managed public lands in Idaho and Montana. Surveys addressed 10 specific management strategies that could be implemented to adapt to climate change; participants were asked to evaluate the likelihood and effectiveness of each of these strategies (Figure 4.3). Actions considered most effective were forest treatments to reduce fire hazard and improve forest health, such as thinning projects aimed at decreasing tree density or removing hazardous fuels, and infrastructure modification, such as replacement of existing roads and culverts to make them less flood prone (Figure 4.3). For example, one interview participant noted that "Upsizing culverts to prepare for earlier spring [snow] melts, or more precipitation falling as rain during that time period where it might be snow instead" could be effective for adapting to climate change. Participants also felt that infrastructure modifications, forest treatments to improve forest health and reduce fire hazard, and prescribed burning were the management actions that were most likely to be carried out by the USFS or BLM in response to potential climate change impacts. Restoration using alternative tree species or varieties that might be more resilient to climate change was considered potentially effective by participants, but less likely to be used by their agencies (Figure 4.3). For example, one manager commented, "we have not gotten into the mode of assisted migration or changing our species that we're planting because of what we think may happen in the future as the climate changes." Finally, participants felt that actions such as forest thinning to increase water availability (e.g., targeted thinning of conifers encroaching into wet meadows or semi-arid shrublands) or the intentional movement of species to areas or habitats predicted to be favorable in the future but currently outside their range (i.e., assisted species migration) were neither likely nor effective (Figure 4.3).

Although a few participants mentioned specific adaptation strategies during the interviews and breakout discussions, most participants felt uncertain about potential management actions that could help their agencies adapt to or mitigate climate change. "I think we are challenged to sort out what [to do] about climate change... we don't really know what we can do... I think we all realize that we are sort of bystanders to this," said one participant. Consistent with the surveys, participants who discussed specific management treatments for adapting to climate change in their interviews focused on using familiar techniques (e.g., thinning, prescribed burning).

Nearly half (46%) of the interviewees emphasized increasing "resilience" of forests for multiple objectives in their comments about how climate change adaptation might occur. Increasing resilience was also a common theme of group discussions during the workshops. For example, a planner with the BLM mentioned that the agency is "trying to make sure our streams are as resilient as possible—[so we do a lot of restoration activities to] remove the stream barriers, fish barriers, things that would warm temperatures..." Another planner mentioned that because climate change is "an uncertainty that we can't necessarily predict and/or manage for," the best management option might be to manage for a diversity of "[tree] age classes and species" to have something that might be "resilient in the future." Resilience has been emphasized in many of the federal climate change policies, and this concept seemed to resonate with resource managers' thinking about potential adaptation strategies.

Several participants expressed frustration that the amount of land they could effectively treat would be minimal compared to the potential impacts of climate change. "I'm looking at a map right now... and I'm [thinking] I could do something on the ground that would cost a bunch of money [and it] would be great, but in the grand scheme of things, it would only be a tiny, tiny piece of ground that I'm actually doing any good on," commented one ecologist. Participants also recognized that the scale of land management being done currently might not be effective in mitigating climate change (i.e., reducing carbon emissions). For example, one forester from a regional USFS office noted that because of the extensive vegetated area his agency manages, "there are carbon storage issues that we could deal with in terms of reducing fire hazard and the large mass of carbon released from wildfire events." However, this forester went on to comment that social barriers (e.g., litigation by environmental interest groups) limit the amount of area they can effectively treat. Because of these limitations, resource managers felt that they would instead be forced to adapt their management to deal with the impacts of climate change after the fact. "Our projects aren't going to affect [climate change] but we will be affected by it, so what is our management going to do to respond?" one participant asked. "Adaptation is probably going to be the key," noted another.

Furthermore, although previous policy has guided land management to consider historical reference conditions as a baseline for restoration, a few of the interviewees recognized that, in light of climate change, restoring to those conditions might no longer be a viable goal. For example, one silviculturist stated that "the thinking [in the USFS]... has been that if we restore things to within the historical range of variability, we somehow increase resistance and resilience to change. Now, we have to construct what could be the [future] ranges that will function with climate change." Seventy percent of participants surveyed prior to the workshop agreed that their agencies might be willing to explore alternative management solutions beyond restoring to reference conditions. Nevertheless, the totality of the survey, interview, and workshop data suggest that managers don't know what those solutions should be.

Barriers to use and implementation of climate change science

Our survey included three potential barriers based on the literature: time, funding, and politics (Figure 4.2). Time was mentioned frequently in the workshop group discussions; representative comments included "there is not enough time to learn new tools," and "there are so many other priorities, [that] climate change is just one more thing [that requires] time." Participants also commented that part of the difficulty in using climate change science was keeping up with the wealth of information that is continuously being published, where there is little time to "know all the latest, greatest science that's out there, and to have it readily available at your fingertips." Being able to readily access information in a concise format would reduce some of the perceived barriers participants had with using the science. Participants also elaborated on the issue of funding for climate change adaptation projects. For example, on regional planner emphasized that without "extra resources in terms of capacity or funding, how are [resource managers] supposed to do [anything about climate change]?"

External politics and litigation by public interest groups also appeared in the interviews as a major barrier that participants perceived to limit their ability to manage for the impacts of climate change in the future. Managers noted that much of their energy was devoted to dealing with issues that were of current concern to the public, leaving little time to focus on new issues like climate change. “You can [only] do so many projects and so you don’t spend a lot of time on things that you’re not being challenged on. The climate change [issue] seems to be an emerging issue that we’re not actually pursued on yet. The things that you get pursued on are the ones you start paying more attention to,” one forest planner noted in an interview. Another planner commented that even though “the Washington office [of the Forest Service says] we’re [going to do] more accelerated restoration, and massive thinning [to mitigate for climate change], the reality is we get appealed and then we get litigated.” This planner went on to say that managers “can’t do anything on the ground without getting through the [environmental] issues, [which is] really such a sociopolitical piece of [management].”

Beyond the items included in the survey, participants discussed several other institutional barriers in workshop discussions and interviews related to using climate change science for management decisions. For example, the size of the agencies and the associated bureaucracy means that changes occur slowly and new ideas and management strategies are unlikely to catch on quickly. Comments from USFS employees such as, “the Forest Service is a big machine... with a lot of ingrained ideas of what we do,” or, “because of the bureaucracy, things happen very slowly,” were widespread throughout the group discussions and interviews. Many participants commented that in recent decades agencies have often operated reactively, dealing with issues after they become problems rather than anticipating situations and proactively addressing them. For example, one hydrologist remarked, “It’s not like we are waiting for [climate change] to come in. It’s been here for a couple of decades.

We haven't changed things, really. We're talking about how we're going to do this, and we should be talking about how we should have done this." Although slow, some participants were optimistic that changes in ingrained management practices would eventually occur. One participant gave this example, "To change livestock grazing, for example, [might be] kind of a hard thing to do, but it seems like when people aren't meeting permit stipulations that things will have to change. It might take a while before they realize actually that this is not just a weird year, this is a weird decade, [and] we are still not meeting targets year after year."

Additionally, several participants noted a lack of organizational capacity to address climate change; that is, people are not trained and/or educated about climate change and there is no time or funding to support this effort, and, even if managers have the training, the expertise, or the inclination, the support and direction from higher levels may be lacking. One forest planner acknowledged that "[Climate change] is a stated policy of the Forest Service, there's no question about that. But that doesn't mean every district ranger, every forest supervisor, believes in it. That then gets reflected in their program of work and what they emphasize." Another manager relayed a similar view: "We have the people, we have the experience and expertise and technical savvy to get this done. We need the support to be able to do it." Participants emphasized that upper-level decision makers (e.g., district rangers, forest supervisors) had the final say on what projects get done on national forests and rangelands, therefore, it was "up to [the decision makers] to decide whether they want to take a risk or not [to do something about climate change]." Poor organizational support meant that these managers had little motivation to incorporate climate change into their planning efforts unless they were getting specific direction from these line officers.

Discussion

Many of the federal resource managers we interacted with from Idaho and western Montana USFS and BLM offices think that climate change science could be useful for the work they do, demonstrating that they consider climate change to be a salient issue with the potential to impact the resources they manage. Except for brief and oblique mentions of "climate change resilience" in land-use plans, few of the public land managers we surveyed indicated that they were actively using climate change science in their work. This result is likely to vary depending on the specific district or forest that individuals work on; for example, other national forests and BLM districts, such as the Okanogan-Wenatchee, Colville, and Olympic National Forests, in the nearby state of Washington, have been proactive about incorporating climate change science into forest-wide strategic plans (West et al. 2009, Halofsky et al. 2011) and are likely to have much more comprehensive guidelines in place for addressing the impacts of climate change in their planning efforts. However, our findings were consistent with results from interviews with natural resource managers in the southern Rocky Mountains about the usefulness of climate change science (Ellenwood et al. 2012), suggesting that the integration of climate change science into management planning may still be evolving.

The usability of climate change science is influenced by whether an appropriate scale of information exists and if the science is informative within the specific end-user decision making context (Dilling and Lemos 2011). Our results indicate that science at temporal and spatial scales that matched the scale of project planning was an important consideration when participants were evaluating the usefulness of climate change science. In our workshops, local- to regional-scale information that emphasized risk management and long-term planning, such as watershed projections of changing precipitation phases (Klos et al. 2014), monthly streamflow, and flood risk (Hamlet et al. 2010), were considered especially useful by resource managers. Downscaled climate change projections that focus at sub-regional scales and project impacts over shorter time frames are likely to be much more applicable to managers' goals (Letson et al. 2001, Rayner et al. 2005, Dilling and Lemos 2011, Archie et al. 2014). Where these resources can be made available through freely available outlets such as websites or personal blogs, they are more likely to be successfully accessed and applied to project planning (Archie et al. 2014).

Science that is "co-produced" between managers and scientists and tailored for specific resources or targets potential actions has also been shown to effective in overcoming informational barriers (Lemos and Morehouse 2005, Joyce et al. 2009, Dilling and Lemos 2011, Kocher et al. 2012, Littell et al. 2012, Moss et al. 2013). This approach has been used effectively in wildland fire (Kocher et al. 2012) and water resources management (White et al. 2008, Wilder et al. 2010). For example, hydrologic studies indicating the quantity or timing of available water sources can dictate how water is allocated for agriculture, development, or other uses (e.g., White et al. 2008). In its application to wildland fire management, forecasts informed by current science are used to allocate appropriate resources for the coming fire season. Science that focuses on management-relevant objectives and needs, such as information on fuels and long-term weather forecasts, is used to make decisions in the face of uncertain potential outcomes (Lemos and Morehouse 2005). Organizational structures that help bridge the boundary between science and management (e.g., boundary organizations) are likely to be key in maintaining an environment where scientists and managers can continually discuss relevant needs (e.g., White et al. 2008). In some cases, these structures already exist in the U.S. northern Rocky Mountains, where USFS funded Collaborative Forest Landscape Restoration Projects encourage collaborative, science-based ecological restoration. Though the goal of these organizations is not climate change adaptation, per se, as these organizations become institutionalized, they could serve as effective vehicles for knowledge production and sharing across administrative boundaries (Gaines et al. 2012). Approaches such as single or multi-day workshops or focus groups may also be effective for helping managers develop general adaptation strategies to deal with climate change (Littell et al. 2012, Blades 2013).

While climate information at management-relevant scales is starting to become available in the research community, access to that information may still be an issue for managers looking to use this information (e.g., White et al. 2008). Where information is accessible, it is often in a format that is difficult for managers to digest and apply. Several participants stated that they had neither the time nor the expertise to sort through the climate change science that is currently available. National forests have attempted to bridge this gap by creating regional and forest-specific climate change coordinator positions (Tribbia and Moser 2008). These individuals are responsible for collaborating with scientists to create, compile, and disperse regional climate change science relevant for each forest. However, the degree to which this task is effectively carried out often depends on the individuals, their motivation, and their other job responsibilities. This variability was evident in our study; participants in one workshop location were well informed about climate change projections and impacts due to effective communication between their regional climate change coordinator and personnel at the forest and district levels. However, participants in other workshops were not nearly so well informed. Prior studies have emphasized the importance of colleagues as information sources for federal resource managers (Tkacz et al. 2010), thus, well-informed climate change coordinators and line officers may play an essential role in getting climate change science incorporated into day-to-day land management activities (Archie et al. 2014).

In addition to a lack of management-relevant information, specific agency guidance, lack of resources (e.g., time, funding), and public support were the most frequently mentioned constraints when our study participants were asked to elaborate on barriers that prevented their use of climate change science. Although we did not separate responses from BLM or USFS participants, prior studies indicate that these agencies may face similar challenges. Specifically, lack of information at relevant scales and budget constraints were cited by both BLM and USFS employees as perceived barriers to adaptation planning (Archie et al. 2012). Furthermore, lack of agency guidance or direction is cited as one of the biggest limitations in prioritizing climate change in land management decisions (GAO 2007). Specific agency direction was a more significant barrier for individuals from the BLM than the USFS (Archie et al. 2012), though we heard from USFS and BLM participants alike that the necessary support and guidance from line officers and decision makers at the planning unit or forest level was currently lacking. Time, funding, and internal and external politics are also barriers to using scientific data and information in land-use planning and management (e.g., Dilling and Lemos 2011, Mukheibir et al. 2013). The managers participating in our study felt their agencies were reluctant to commit time and money to projects when there is uncertainty about the magnitude, timing, or probability of a climate change impact. Finally, several of our study participants felt that climate change was not yet a high profile public issue, and was therefore unlikely to be prioritized within current management. Management priorities are often shaped by public opinion (Archie et al. 2012, Ellenwood et al. 2012), especially because public comment is required by NEPA for any management activity that has potential ecological impacts. Competing priorities may limit how much time resource managers feel they can allocate to training, education, or synthesis of climate change science (GAO 2007, Jantarasami et al. 2010), while also impacting the likelihood that climate change adaptation projects will be funded, implemented, and publically supported.

While recent federal policies guide managers to consider the implications of climate change at all levels of land management planning, most managers we interviewed are not yet thinking about or addressing climate change directly with specific projects. Of the particular management actions addressed in our surveys, participants generally felt that existing management strategies (e.g., thinning, prescribed burning) would be the most effective and likely to be implemented in response to climate change (Figure 4.3). Management actions that are already widely implemented on public lands to meet other objectives are more likely to be supported by decision makers and have relatively little risk of eliciting negative public opinion (GAO 2007), which can be the key to success in a land management agency that must respond to both public input and litigation. For example, former lawsuits that resulted in legal decisions regarding certain management actions may set a precedents that allow managers to know what existing management actions they can take without being formally challenged. Additionally, using existing policies, where applicable, would allow agencies to meet multiple goals without having to necessarily anticipate the future extent and timing of climate-related impacts (Joyce et al. 2009). The Healthy Forest Restoration Act of 2003 (PL 108-148), for example, allows increased forest thinning and prescribed fire to reduce hazardous fuels and wildfire. This policy could be used as support for ongoing and accelerated restoration and fuels treatments that increase forest resilience to disturbance-related impacts of climate change.

Novel adaptation strategies, such as assisted species migration, expanding the genetic stock for revegetation, or managing for future insect and disease outbreaks (e.g., Joyce et al. 2008), on the other hand, were rarely discussed in interviews or workshop discussions, and surveys indicated that most resource managers felt these strategies were unlikely to be implemented by the USFS or BLM. Even though these adaptation strategies might be effective for dealing with climate change, they require anticipation of the timing and extent of future shifts in, for example, species composition or the frequency of extreme events (see Joyce et al. 2009). Many managers recognize the non-linear nature of ecological responses and the stochasticity of disturbance events, which may lead to their reluctance to adopt strategies that rely on future climate and species distribution projections (Joyce et al. 2008). Likewise, extensive monitoring, changes to existing policies and regulations, or adoption of new policies may be required to make novel adaptation strategies a more feasible option (Joyce et al. 2008). For example, although management activities such as assisted migration have been effective in a few trials aimed at eliminating the risk of species extinctions (Joyce et al. 2008) or expanding ranges for commercially valuable timber species (e.g., Willis et al. 2009), there are still tremendous political and ethical ramifications of planting species outside their naturalized range (e.g., Pedlar et al. 2011), and there is little policy guidance when and where this adaptation strategy is appropriate (McLachlan et al. 2007, Schwartz et al. 2012).

Uncertainty about the potential impacts of climate change led many of our participants to focus on general goals or outcomes rather than specific management strategies, such as managing forests and rangelands to be more resilient to future climatic changes. Resilient ecosystems are those that have a greater capacity to gradually respond to climate perturbations or recover more rapidly after disturbance (McLachlan et al. 2007). Although management over the past several decades has often focused on restoring resilience by returning the landscape to historical reference conditions, climate change may necessitate a different approach (Millar et al. 2007, Hobbs et al. 2014). Therefore, guidance is needed to define what ecosystem resilience may look like with potential future changes in climate (West et al. 2009). Basing management decisions on unknown future conditions makes decisions challenging, but proactive adaptive management approaches such as increasing structural and compositional diversity of existing ecosystems, improving connectivity of landscapes for species' migration, and intensive monitoring and treatment after active management are some solutions that have been suggested to allow resource managers flexibility in response to climate change (West et al. 2009). These strategies don't require local-scale or species-specific projections to implement and can be informed by existing ecological knowledge. However, these solutions may only be viable so long as major ecosystem transitions do not occur. Over the long-term, management approaches may need to shift with shifts in ecosystems and resources (Millar et al. 2007, Joyce et al. 2009, West et al. 2009).

Conclusion

Although the science on potential climate change impacts continues to grow and be refined, the types of climate change research resource managers in the USFS and BLM perceive to be available and accessible are not currently effective for creating management prescriptions. However, rather than uniformly increasing the supply of climate science, federal land managers need a process in which they can repeatedly and collaboratively interact with scientists in production and compilation of climate change science that is usable and applicable (Dilling & Lemos 2011). These collaborative efforts could alleviate perceived barriers associated with lack of personnel and resources to develop the information independently (Archie et al. 2014). Federal resource managers desire scale-relevant research focused at sub-regional scales (Archie et al. 2014). Projections that focus on impacts that have direct applicability to management priorities, such as projections about vulnerabilities to fire, flooding, or habitat loss may be perceived as more useful. As peer reviewed journals are not easily accessible or readily used by federal land managers (Archie et al. 2014), having information available on regularly updated websites or blogs could be an important way to ensure its accessibility. Additionally, federal land managers could benefit from workshops, webinars, or trainings that serve as boundary objects for synthesizing relevant information and aim to bridge the research-management gap. The framework for these boundary organizations may already exist in Collaborative Forest Landscape Restoration Programs, Landscape Conservation Cooperatives, and other efforts in place nationally and across the U.S. northern Rocky Mountain region. These organizations could play an active role in disseminating climate change science, and serve as fertile ground for future research about the effectiveness of boundary objects and organizations.

Having appropriate information is only one part of the challenge of effectively managing for the impacts of climate change. Knowing how to apply that information and having the support and resources to take action are also essential. On public lands managed by the USFS and BLM in the US northern Rocky Mountains, there is a disconnect between mandates at the national level and actions that are being taken at the district or field office level. While national policies for climate change adaptation and mitigation are in place, resource managers still lack the specific guidance and support from decision makers in upper management that would allow them to start managing for climate change impacts. Although there is significant uncertainty associated with managing for climate change impacts, low risk options, such as more widely applying current techniques, may be an easy and effective way to begin to implement climate change adaptation measures on-the-ground (Joyce et al. 2009). These options can be informed by existing regional-scale climate change projections that focus on predictions of potential risks (e.g., to increased frequency of wildfire, flooding). In the short term, focusing on where existing treatments can accomplish multiple goals could reduce costs while stretching limited resources. Adapting existing policies to facilitate climate change adaptation may also allow management flexibility and rapid response measures (Joyce et al. 2009). Collaborative efforts between public, private, and non-profit organizations can increase the suite of viable adaptation options for resource managers by heightening public support and providing guidance on managing more extensive landscapes. Finally, over longer time scales, it will be important to invest in additional research and monitoring on management strategies that are considered potentially effective but are currently not widely implemented as this may increase the probability of their future adoption by agencies.

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Table 4.1. Mean score for each statement about the usefulness of climate change (-3 to +3, strongly disagree to strongly agree) ± 2 standard errors. An ANOVA with Tukey's post hoc tests was performed to determine the statistical significance of differences in mean ratings between each type of information. Superscripts that differ indicate values that differ at alpha = 0.05. N indicates the number of responses to each prompt.

Items	N	Mean ± 2 SE
The global climate change information is useful for land management (modeling and emission scenario information).	60	1.4 ± 0.2^a
The regional climate and water research is useful for land management.	61	2.2 ± 0.2^b
The regional vegetation and fire research is useful for land management.	59	2.2 ± 0.2^b
The local-scale forest vegetation and climate simulations are useful for land management.	58	1.9 ± 0.2^b

Figures

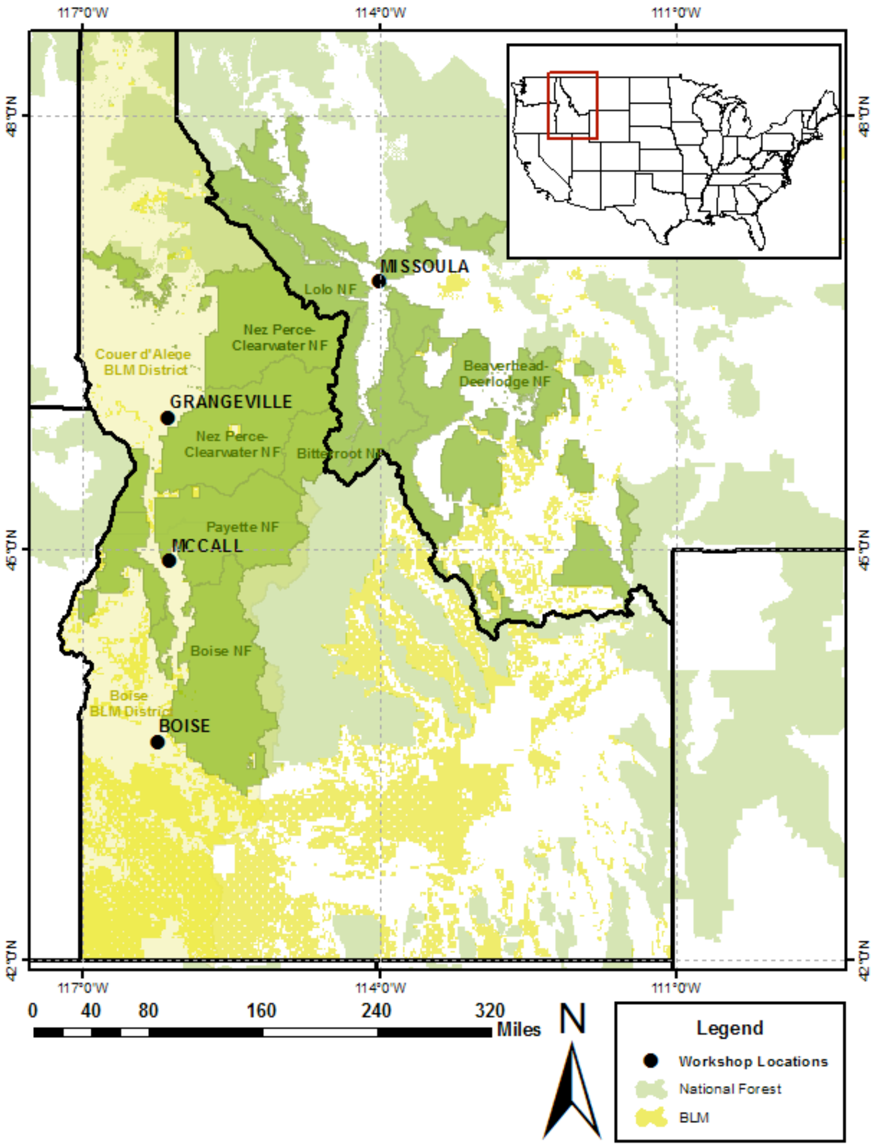

Figure 4.1. Map of the study area highlighting the National Forests (dark green) and Bureau of Land Management (BLM) districts (light yellow) represented by workshop participants. Participants were from six national forests and two BLM districts. The majority of land area in the U.S. northern Rocky Mountains (defined here as Idaho and western Montana) is federal land under the control of the US Forest Service (light green) and BLM (bright yellow).

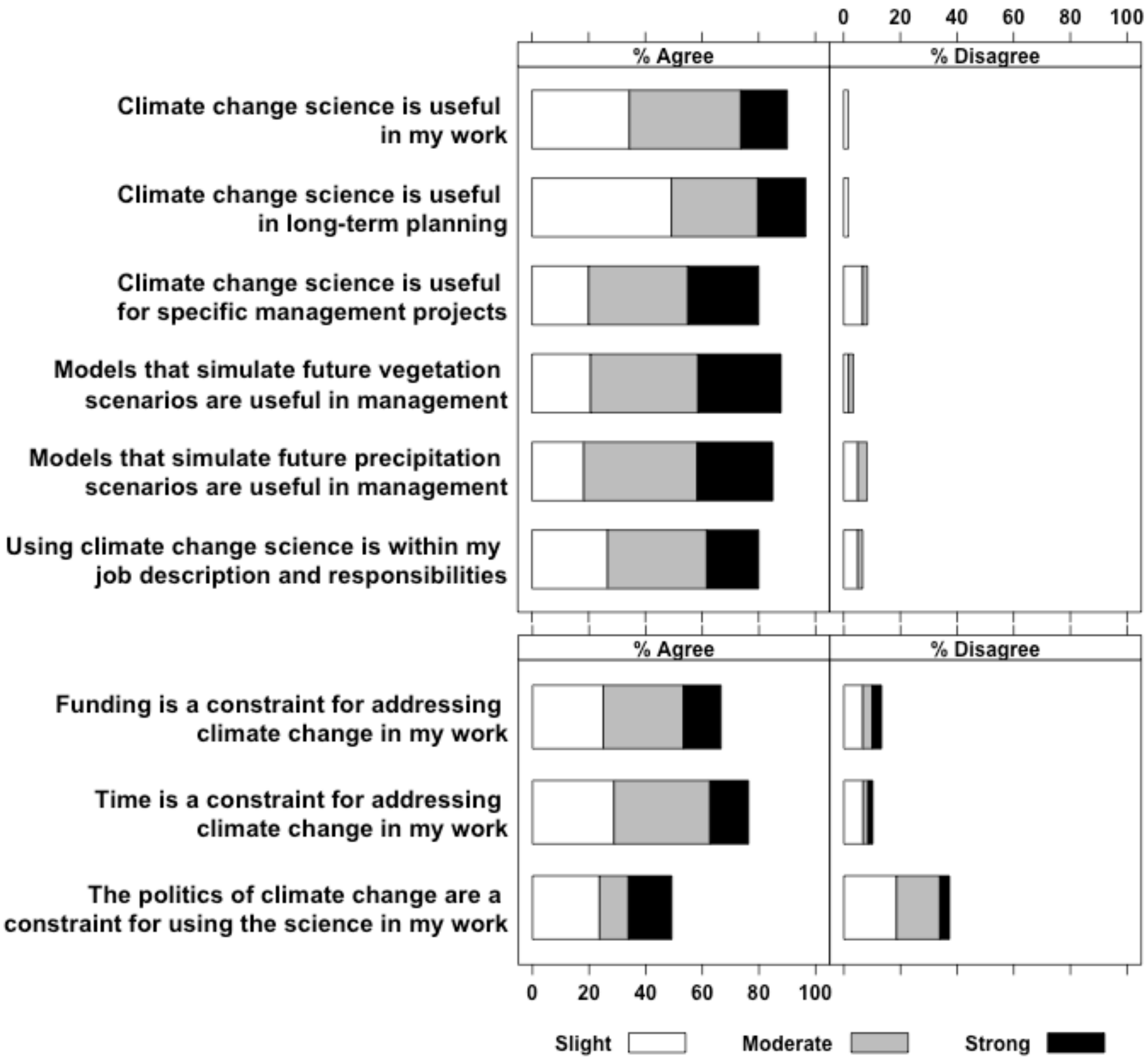

Figure 4.2. Percentage of survey participants that agreed, felt neutral, or disagreed with the statements in the pre- and post- workshop interviews regarding the usefulness of climate change science (top panel) and barriers to using the science to adapt or mitigate the impacts of climate change (bottom panel). The "Agree" column displays the percentage of participants that strongly agree (-3; black bars), agree (-2; grey bars), or slightly agree (-1, white bars) with the listed survey statements. The same is true in the "Disagree" column. Neutral (neither agree nor disagree) responses are not displayed, thus, bars may not sum to 100%.

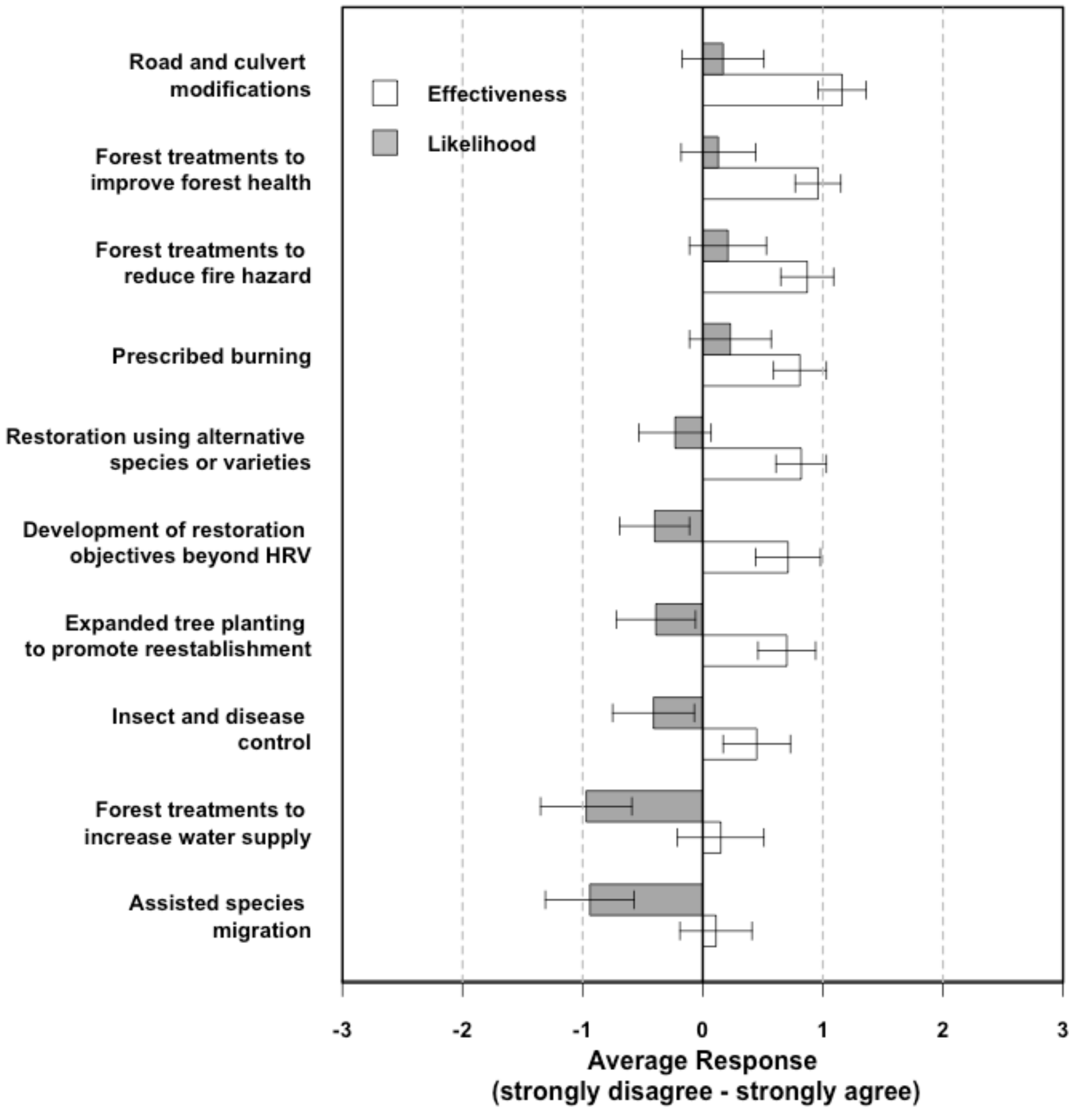

Figure 4.3. Mean response to ten survey questions asking participants (n = 61) to evaluate the efficacy of different management strategies for adapting to climate change in Idaho and Western Montana. Participants were asked to rate whether they felt they actions listed would be effective (white bars) and the likelihood that their agency would use each action (grey bars) to adapt to the impacts of climate change. Responses were scaled from -3 (very ineffective/unlikely) to +3 (very effective/likely). Management actions that were more likely to be considered effective and likely to be implemented in response to climate change are at the top of the figure. Actions that were perceived to be ineffective and have a low likelihood of implementation are at the bottom of the figure. Error bars indicate ± 2 standard errors around the mean. HRV stands for Historical Range of Variability and refers to the range of potential conditions (e.g., disturbance, climate) that a particular ecotype may have experienced prior to European settlement and heavy anthropogenic manipulation of the landscape

CHAPTER 5

Forest managers response to climate change science: Evaluating the constructs of boundary objects and organizations

Jarod J. Blades, P. Zion Klos, Kerry B. Kemp, Troy E. Hall, Jo Ellen Force, Penelope Morgan, and Wade Tinkham

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Abstract

Land managers lack locally relevant climate change science and are urgently calling for research to inform management. We conducted four climate change workshops in the U.S. northern Rocky Mountains and applied multiple methods of inquiry to understand whether the boundary organization (workshops) and objects (climate change science products) were perceived as credible and useful. Perceived credibility and usefulness increased overall, and regional-scale hydrologic information was deemed most useful. Regression models found that intention to use climate change science was predicted by usefulness, credibility, and organizational barriers. We discuss the importance of uncertainty,

visualization, and best practices for effective climate change deliberation using boundary objects and organizations at the research-management interface

Introduction

Climate change represents one of the greatest challenges to land management and society. There is strong evidence of climate changes that have impacted biophysical systems in the past, as well as how these challenges are anticipated to impact our future (Environmental Protection Agency, 2010). They are expected to further alter the mountainous ecosystems of the U.S. northern Rocky Mountains and continue to affect the people who depend on them for ecosystem services and livelihoods. Land management agencies will not be able to fulfill their missions to promote sustainability without integrating climate change impacts into management plans and actions. With rapid biophysical changes already occurring in these forests, the United States Forest Service (USFS) and other stakeholders are increasingly seeking to understand and mitigate the effects of a changing climate. Historical data from the northern Rockies region have indicated moderately to highly significant shifts in vegetation growing-season length, annual temperature, amount of forest area burned, lilac phenology, mountain bluebird phenology, precipitation intensity, timing of streamflow, and April 1st snowpack levels – many of which could have important consequences for how our forests, fires, and other natural resources are managed in the future (Klos *et al.*, In Press). Although forest managers are mandated to use climate change science in their management planning, few managers in the northern Rockies have been found to be actively using this information because of perceived barriers in information quality and quantity (Kemp *et al.*, 2015). Effective action depends on having open and reasoned discussions among land managers and researchers in order to understand the implications of climate change and potential mitigation actions (Hall *et al.*, 2012; Dietz, 2013). Recent research has called for communication efforts to shift messages about climate change from a frame of “uncertain science” and a “Pandora’s Box” towards new cognitive reference points that connect climate change to something locally specific the audience already values or understands (Nisbet and Kotcher, 2009). To answer this call in a forest management context, we engaged forest managers in a deliberative and interactive way with the intent of strengthening the overlap between regional climate change research and end-user information needs and improving forest adaptation to climate-related impacts.

In the fall of 2012, our interdisciplinary research team of biophysical and social scientists conducted a series of climate change workshops (CCWs) focused on conveying locally relevant information on shifts in forested landscapes due to changing climate. The CCWs facilitated the exchange of current climate change knowledge across research and management boundaries in the U.S. northern Rocky Mountains. Our CCWs were designed to communicate abstract concepts of climate change impacts at regional and local scales by synthesizing historical data and visualizing model-generated forecasts of future changes to forest and water resources.

To assess how participants’ attitudes and beliefs changed as a result of CCW participation, we applied a pre-test/post-test, mixed methods approach. This study contributes to both theory and practice of boundary objects and organizations by carefully analyzing constructs that have been posited as leading to more effective decision outcomes. Additionally, we incorporated ideas from social learning theory to develop activities likely to enhance collective understanding in the application of science to practice, including visualization techniques. The objectives of this study were to: 1) describe the background and need for using boundary objects and organizations, including the hypothesized effects of CCW participations and relationships between boundary constructs; 2) explore how the workshops and tools were constructed and evaluated within a boundary theory context; and 3) evaluate the observed change as a result of CCW participation, the relationships between variables, and the overall effectiveness of our boundary objects and the CCWs as a mechanism for the rapid transmission and use of climate change science in land management decisions.

Background and need for boundary organizations and boundary objects

The process by which research communities establish relationships with the worlds of land management and policy is commonly referred to as boundary work (Gieryn, 1983; Clark *et al.*, 2010). Boundaries are symbolic distinctions that categorize objects, people, practices, and even time and space (Lamont and Molnár, 2002). Boundaries have been addressed in two ways: through the concepts of boundary organizations and boundary objects.

Boundary organization theory offers one approach to understanding and enhancing interactions between the different worlds of specific groups or organizations. Boundary organizations – institutions or settings that facilitate knowledge and information exchange among scientists, decision-makers, and land managers – can facilitate a multi-directional flow of information between science and management at multiple scales (Cash and Moser, 2000). The primary assumptions of boundary organizations set forth by Guston (2001) are: 1) they exist at the frontier of the science and management communities but are accountable to both; 2) they involve participation by land managers/policymakers and researchers, as well as professionals who mediate between them; and 3) they provide opportunities for the co-production of boundary objects, which are tools that serve useful function to multiple professional worlds. In the context of climate change, research specific to boundary organizations is relatively new, but important, because the pace of climate change research is growing. Land managers need information specific to their regions, and boundary work provides a mechanism for integrating academic research products with practical land management needs.

In a separate line of work, researchers have explored boundary objects – hybrid, flexible, and portable tools that help people from multiple sectors negotiate knowledge transfer between the science, management, and policy realms (White *et al.*, 2010; Cutts *et al.*, 2011). Model-based decision support tools have become popular as boundary objects that connect natural resource sciences and decision-makers, because models provide a means for visualizing complex information and exploring different management scenarios (White *et al.,* 2010). We defined our boundary organization as the CCW as a whole, and the boundary objects were the climate change information, including modeling tools, used during the CCW.

Despite the interest in and promise of boundary organizations and objects, the different types, natures, and effects of boundary objects in natural resource management are poorly understood (White, 2011). Cash *et al.* (2003) identified three elements integral to linking knowledge and action for environmental decision-making: credibility, salience, and legitimacy. ***Credibility*** involves the scientific adequacy of the technical evidence and arguments. This has been qualitatively assessed in terms of perceived scientific accuracy, validity, technical evidence, data quality, calculations, and visual display (White *et al*., 2010). ***Salience*** (or usefulness) is the perception of whether the boundary object has the ability to meet the needs of decision-makers. ***Legitimacy*** reflects perceptions that the production of information and technology has been respectful of the divergent values and beliefs of stakeholders. In our study, these constructs were evaluated in terms of both the CCW organization and individual boundary objects.

Institutional environments also affect the capacity to use climate change science in land management. Agency policies, directives, diverse priorities, time, funding, politics, and litigation are a few potential barriers that may supersede the previously described variables related to boundary objects and organizations (Jantarasami *et al.*, 2010; Archie *et al.*, 2012). The more barriers a person perceives, the lower his/her intention to use climate change research in land management.

Our pre- and post-workshop interviews and questionnaires were designed to evaluate the effect of the boundary organization and objects, and explore the hypothesized relationships between the factors that predict likelihood to use climate science in forest management. The specific hypotheses we tested were the following:

H1: Perceptions of (a) the usefulness and (b) credibility of climate change science in forest management will significantly increase as a result of participating in the CCWs.

H2: Greater perceived credibility will be associated with greater perceived usefulness of climate change science in forest management decisions.

H3: Greater perceived usefulness will be associated with greater intention to use climate change science in future forest management.

H4: Greater perceived organizational barriers will be associated with (a) lower perceived usefulness and (b) lower intention to use climate change science in forest management decisions.

H5: The effect of credibility and organizational barriers on behavioral intention will be mediated by the perceived usefulness of the science.

H6: Participation in the CCW will result in a positive overall evaluation of the credibility, salience, and legitimacy of the boundary organization.

Methods

Workshops as boundary organizations

The overall CCW represented a boundary organization existing at the frontier between the science and management communities and involved participation by actors from both communities (Guston, 2001). Our CCWs met the assumptions of boundary organizations because: 1) the workshops were conducted with USFS personnel (including decision-makers), academic researchers, and regional collaborative group members; and 2) the tools used in the CCW were developed and used by professionals from both the scientific and land management worlds (Figure 1).

Recognizing human limitations related to attentional capacity, information processing ability, and cognitive load, we carefully considered the design and presentation of climate change information during the workshops (Figure 2, Figure 3). Transforming abstract numeric and verbal data into imagery can greatly reduce the risk of confusion while honoring the inherent human preference for visual information (Al-Kodmany, 2002; Sheppard, 2005). Therefore, we emphasized visualization of climate change trends and impacts in order to summarize a large amount of complex information and make the information locally relevant (e.g., Lipkus, 2007; O'Neill and Nicholson-Cole, 2009). Visualization also helped to convey the uncertainty of complex information in a way that participants can process (MacEachren et al., 2005; Schroth et al., 2011) (Figure 3).

The CCW tools represented and satisfied the assumptions of boundary objects because the tools could each be freely used by different actors in different locations, they model and predict future scenarios, they explain the meaning and significance of climate change effects in forests of the northern Rocky Mountains, and they provide a foundation for climate change discussions among people from different disciplines and sectors (Star and Griesemer, 1989). The boundary objects went through integration and co-production between our research team (the scientific community) and managers (USFS and forest collaborative groups). The final boundary objects represented diverse information, compiled at different scales:

1. *Global Scale*: An overview of global climate, including both historical (geologic and contemporary) reconstructions and future projections of atmospheric CO_2 concentrations. The greenhouse effect, emission scenarios, and general circulation models (GCMs) were also explained.
2. *Regional-Scale Water Resources*: Historical data on changes in temperature, precipitation, snowpack, streamflow, and stream temperature within the northern Rocky Mountain region over the past century (Klos *et al.*, In Press). Future projections and three-dimensional animations showed how these systems may continue to change (Klos *et al.*, 2014).
3. *Regional-Scale Forest and Fire Ecology*: Bioclimate envelope models were used to display potential future biome and tree species distributions in the northern Rocky Mountains (Rehfeldt *et al.*, 2008). Wildfire-climate projections visualized increases in area burned in the

western U.S. (Littell, 2011), increasing fire season length (Klos *et al.*, In Press), and days with high fire danger ratings (Abatzoglou and Kolden, 2011).

4. *Local-Scale Vegetation Simulations*: Simulations of different management scenarios were run using the Climate Extension to the Forest Vegetation Simulator (Climate-FVS) (Crookston *et al.*, 2010) to provide forest managers a tool for considering climate change effects on forests at the stand level.

In addition to the boundary object variables described above, we recognized the need to employ best practices related to active/collaborative learning and small group processes during the CCWs (Daniels and Walker, 1996; Michael, 2006). We desired active engagement between workshop participants, with the opportunity for them to work together in small groups and articulate their understanding and opinions to others. Thus, we facilitated breakout discussions so that participants could carefully reflect upon the climate change science, consider how it might be useful in land management, and identify where gaps exist.

According to boundary organization theory, successful exchange of the climate change information during the CCWs was more likely to occur if the workshops and modeling tools were perceived as credible, legitimate, and salient.

Design and sampling

We employed a mixed sequential equal status design (Leech and Onwuegbuzie, 2009) to triangulate quantitative and qualitative data in the evaluation of our CCW boundary organization and objects. Qualitative interviews provided depth and richness to our understanding of the utility of climate change science in land management, while quantitative surveys permitted us to establish the magnitude of relationships among constructs.

The CCWs were quasi-experiments because the participants were self-selected (i.e. lacked random assignment) and we did not attempt to isolate the effects of the pre-test or use a control group (Creswell, 2009). Our interrupted time series design involved pre-test measures (i.e. interviews then questionnaires), a treatment (i.e. the workshop), and post-test measures (i.e. questionnaires then interviews).

We purposefully selected individuals who satisfied multiple criteria (listed below) to maximize our understanding of the effectiveness of our CCWs. Using a snowball sampling approach (Creswell, 2009), we asked participants to recommend other participants, including both climate change accepters and deniers. The sample frame involved selecting U.S. National Forests that were: 1) located within the northern Rocky Mountains (Idaho and Montana); 2) contained a steep elevation gradient with a diversity of forest types; 3) were identified as being sensitive to substantial temperature and precipitation changes (Klos *et al.*, 2014); and 4) had local and regional forest collaborative groups of citizens who were engaged with USFS activities.

For each CCW location, participants were selected from three strata: forest managers/ decision makers and planners (e.g. fire management officers, district rangers, interdisciplinary team leaders, National Environmental Policy Act document editors), forest ecologists (e.g. silviculturists, foresters, fire ecologists), and water resource specialists (e.g. hydrologists, fisheries biologists, riparian ecologists). These strata represented the main natural resource and climate change topics presented during the CCWs (forest, fire, and water resources) and included individuals who regularly work with land management documents that incorporate climate change science. A target of 25 participants at each CCW location (100 total) was chosen to detect a moderate (Cohen, 1988), one-tailed relationship between our constructs of interest with 0.80 power at the 5 percent level of significance (Onwuegbuzie and Leech, 2004). Though by quantitative survey standards this is a relatively small sample for correlational or comparative designs, small samples are appropriate for exploratory research and mixed methods quasi-experiments (Onwuegbuzie and Collins, 2007).

To reach theoretical saturation through our interviews we followed the recommendations of Onwuegbuzie and Collins (2007) to include at least three participants per subgroup in a quasi-experimental mixed methods design. Guest, Bunce, and Johnson (2006) found that the majority of themes reach saturation with the completion of 12 interviews. Therefore, because this study involved CCWs in four locations with three disciplinary strata, we conservatively aimed to conduct pre- and post-workshop interviews with 12 people at each location, and 16 in each disciplinary stratum (48 total pre-post interviews).

Interview and survey content

The telephone interviews and online questionnaires both addressed the variables discussed in the introduction, but the interviews were less structured, allowing for probing and elaboration (Morse and Richards, 2002). Each participant was generally asked the same questions in the same order, with some variation in probing questions based on initial responses. Pre-workshop questions pertained to the primary focus of the study, following the theoretical model of Figure 4, such as “how useful is climate change science in the work you do?” Follow-up discussion included probing questions, such as “what about that particular research makes it useful or impedes is usefulness?” Post-workshop interview questions asked participants to evaluate how their thinking changed regarding the credibility and salience of climate change science in their work based on the boundary objects presented at the CCWs. We also asked participants to evaluate the overall credibility, salience, and legitimacy of the CCWs.

For the self-administered written questionnaires, participants had the option of taking the pre-workshop survey either online prior to the actual CCW date, or on site prior to the start of the CCW. All CCW participants were encouraged to complete a written or online survey at the conclusion of each CCW. To ensure maximum participation, we followed a modified version of Dillman's Total Design Method that included an initial email notifying participants that they would receive a request to complete an online survey, an email with a survey link (the electronic survey was deployed using Qualtrics), a follow-up reminder email, and personal phone calls to those who had not completed the survey (Dillman *et al.*, 2009).

The pre-workshop questionnaire had nine sets of questions. Most questions had 5- or 7-point Likert-type response options. The first section asked questions about the salience (i.e. usefulness) and credibility of climate change science that were adapted from previous boundary object work (Jacobs *et al.*, 2009; White *et al.*, 2010; Cutts *et al.*, 2011). Questions were also asked about potential barriers to addressing climate change in participants' work (Wright, 2010). A final section asked participants about their disciplinary expertise, years worked in the northern Rocky Mountains, highest level of education obtained, gender, and political orientation.

The post-workshop questionnaire had six sets of questions, including the questions from the pre-workshop questionnaire pertaining to the usefulness and credibility of climate change science. An additional section asked participants to evaluate the credibility, salience, and legitimacy of the entire CCW (Cash, 2001; Guston, 2001; Miller, 2001; Buizer *et al.*, 2010; Parker and Crona, 2012).

Interview and survey data analysis

All interviews were digitally recorded with permission and transcribed verbatim. Analysis of the interview data followed a team-based strategy to developing a codebook guide (Boeije, 2002; Ryan and Bernard, 2003). An initial list of parent nodes included categories of anticipated themes based on our theoretical framework and interview protocol. After the parent codes were defined, the research team reviewed the codebook and discussed any discrepancies in code interpretations. Using the team-developed parent nodes, two team members coded each interview. The process continued until each coding category had a definition, an example, and rules for application. The acceptable level of reliability was set at Cohen's kappa > 0.80 (Krippendorff, 2004), which was achieved after four rounds of coding. After reliability was established, one coder applied codes to all the interview text using NVivo, version 10.

Our team also established rapport with the participants through prolonged engagement, such as multiple phone conversations, so that they felt comfortable to provide honest and candid answers. A research journal was kept by all members of the research team during the interview process to track responses and events, allowing us to identify any outside events that could have affected interpretation of a participant's interview (Shenton, 2004).

Survey responses were analyzed using the Statistical Package for the Social Sciences (SPSS, 2010) to reduce multi-item measures to indices using factor analysis (direct oblimin rotation) with a Cronbach's alpha reliability coefficient cutoff level of ≥0.70 (Kline, 2011).

Paired sample t-tests were used to determine whether variables of interest changed from pre- to post-test, and one-way analysis of variance was used to determine whether the variables of interest varied by discipline or location. Ordinary least squares (OLS) regressions were used to test the relationships presented in Figure 4. We used Baron and Kenny's (1986) process for testing the mediating effect of salience/usefulness on the relationships of credibility and organizational barriers to behavioral intention. Four conditions must hold true to establish meditation. First, the independent variables must significantly affect the mediator (multiple regression of usefulness on credibility and organizational barriers). Second, the independent variable must significantly affect the dependent variable in the absence of the mediator (regressed behavioral intention on credibility and separately on organizational barriers). Third, the mediator must have significant unique effect on the dependent variable (regressed behavioral intention on usefulness). Fourth, the direct effect of the independent variable on the dependent variable should weaken substantially or even disappear upon the addition of the mediator to the model (multiple regression of behavioral intention on usefulness, credibility, and organizational barriers).

Results

A total of 97 people participated in the four CCWs; however, for this paper we only analyzed responses from the 61 participants who completed all of the pre-test and post-test quantitative measures (Missoula: 19, Grangeville: 15, Boise: 16, and McCall: 11). We also collected 60 pre-workshop interviews and 35 post-workshop interviews. Substantially fewer post-workshop interviews were collected because severe winter conditions and conflicting agency training prevented the attendance of 25 people who had been pre-interviewed. Analysis revealed few differences related to participants' specific discipline and workshop location. Therefore, for the findings presented here we combined all four CCW locations and disciplines into one sample. Quantitative findings are presented in conjunction with selected qualitative interview excerpts to provide richness and context. Again, recall that the boundary objects discussed below are referring to the visualization tools and data presented during the workshops, and the workshops as a whole are considered the boundary organization.

Credibility of climate change boundary objects

Participants found global and regional climate change science to be significantly more credible than local (forest stand-level) climate change science both before ($t_{52} = 6.9, P < .01$) and after ($t_{57} = 6.8, P < .01$) participating in the CCWs (Table 1). Interestingly, the credibility of both historical data ($t_{55} = 3.9, P < .01$) and projected/modeled data ($t_{55} = 4.3, P < .01$) increased to a similar degree as a result of the CCWs. Many participants commented that the historical data we presented made them more aware that climate change is currently affecting forests they manage, not just something that will happen in the future. One manager remarked how the CCW made her aware that climate change modeling “certainly needs to play a bigger role…because the time frames are a lot quicker than I was thinking going into the workshop.” She felt that they “certainly need to start using [climate change science] in all of our decision making processes” (Manager 4, Boise).

The Exploratory Factor Analysis (EFA) conducted for the five credibility items revealed single reliable dimensions in both the pre-test and post-test (Table 1); therefore, the mean of the items was computed. Perceptions of overall credibility significantly increased because of participating in the CCWs ($t_{60} = 4.01, P < 0.01$).

The interview data reflected the important role of scale in determining whether participants felt the boundary objects were credible. Participants expressed that the scale of the climate change data needed to represent the scale of management to be useful, but mismatches often occur. In discussions about the local-scale modeling, both before and after the CCWs, participants often described an overall lack of confidence in modeling predictions at smaller, project-level scales. For example, one water resources specialist noted before the CCWs that "one of the biggest problems I have with [models is the] validity…it is so out of whack…no way you can say that's going to happen on that acre of ground, on that thirty-meter pixel." He then further described his frustration with the use of models after the CCW by saying, "the data that you used at that broad level, you can't take that same data and take it down right to [a local] scale" (Water/Physical 1, McCall). Though skepticism about the credibility of local-scale modeling was commonly observed before and after the CCWs, participants did indicate that these types of models were helpful for exploring different management actions and illustrating climate change impact trends at regional scales – revealing that sometimes credibility was independent of usefulness. That is, participants may have thought the credibility of local-scale vegetation modeling was low, but that it was still useful for exploring management alternatives.

Further, many participants shared after the CCWs that they were more "convinced of the water [science]…that was presented, and less [convinced] on the terrestrial side" (Water/Physical 10, Missoula), suggesting that the water resources modeling was perceived to be more credible than the vegetation modeling. This was explained by a forest manager in terms of the model complexity inherent in vegetation simulation modeling. He reflected that "the regional [hydrologic modeling] was the most helpful because getting down to the forest level [vegetation modeling] is more microclimate driven… it's harder to transition down to the smaller vegetative scale" (Water/Physical 7, Grangeville). Model complexity and spatial scale were clearly influencing perceptions of boundary object credibility.

Salience/usefulness of climate change boundary objects

Before the CCWs, participants recognized the utility of climate change science for the work they do, especially for long-term land use planning (Table 2). However, many participants attended our CCWs because they wanted a better understanding of the local- and regional-scale context of climate change science, including tools that they could consistently use agency-wide. Participation in the CCW increased ratings for four of the five "usefulness" survey questions. Additionally, salience/usefulness items on the post-test all had mean values >1.0 (agree), suggesting that the boundary objects were perceived as useful.

The exploratory factor analysis (EFA) conducted for the five usefulness items revealed two dimensions with good reliability in both the pre-test and post-test (Table 2): 1) general usefulness of climate change science for planning, and 2) the usefulness of models that simulate future vegetation and precipitation. Using indices computed as the mean of items loading cleanly (≥0.40) on each factor, participant perceptions of the usefulness of climate change science for planning significantly increased as a result of participating in the CCWs ($t_{60} = 1.9$, $p = 0.05$); however, perceptions of the usefulness of models did not increase.

Interviews indicated that participation in the CCW and exposure to boundary objects helped participants see how climate change science could be applied to land management decisions. For example, before the CCW, one participant noted that he had "yet to see a user friendly tool that is easily accessible," but after the CCW, he reflected that "being able to look at the models and kind of see the trend" was "really useful" (Water/Physical 8). The information was something he could share with his crew and "get them thinking in the direction we are going."

In the post-test survey, participants were asked to evaluate the usefulness of different spatial scales of climate change science presented at the workshops. Overall, the regional-scale water ($m = 2.2$) and vegetation/wildfire science ($m = 2.2$) was considered to be significantly more useful than global-scale ($m = 1.4$, $t_{61} = 8.5$, $P < .01$) and local-scale ($m = 1.9$, $t_{61} = 4.1$, $P < .01$) climate change science (Table 2).

Organizational barriers to using climate change

Participants agreed that using climate change science in land management was consistent with their organizations' missions and within their job descriptions. However, the interviews revealed that, until recently, climate change has not been considered a high priority when compared to other natural resource issues, such as special status species, wildland fire, or noxious weeds. Organizational barriers were clearly a factor for using climate change science in management decisions. Workshop participants generally agreed that the organizational barriers of time, funding, and politics are a constraint for using climate change science in their work (Table 3). The EFA conducted for the three organizational barriers items revealed a single dimension with high reliability, so a single factor was computed.

The interviews provided context for perceived barriers; for example, one participant noted that "so many times here [at] the district level you're caught in the deadlines or timeframes and [to] get [a] project put out at [a] particular time, you don't have the time to build in all the literature and to track [climate change research], that is if you have any other kind of life (laughing)" (Water/Physical 9, Grangeville). The same participant then went on to describe how the CCW helped address barriers of time, because "having somebody…

collecting the information is very useful… You realize there are things out there that will be quite helpful"; she further reflected that the CCW "gave me somewhere to go for the information that I need to back -- scientifically back -- what I am saying in my documents."

Intention to use climate change boundary objects

Prior to the workshops, participants agreed that they plan to use climate change science in future work, and that opinion did not significantly change as a result of participating in the CCWs. However, after the CCW, participants reported that they were significantly more likely to use the regional climate change boundary objects related to water ($m = 2.0$) and vegetation/fire ($m = 1.7$) than the global models ($t_{72} = 7.4$, $P < .01$) and local-scale vegetation simulations ($t_{70} = 5.0$, $P < .01$). This was reflected during many of the interviews; for example, one water resources specialist noted before the CCW that he had seen climate science used "on broad scale but not on smaller scale, not on project level stuff." After the CCW he described how higher-level agency direction may influence the use of climate change science: "there is a lot of talk on how you could use [Climate-FVS], and there's a lot of interest [in] that; I think we just don't have a real good handle on how to use it as an agency, except on a very broad regional scale" (Water/Physical 5, McCall). This was consistent with our findings related to the usefulness of climate change science – that science at regional scales is more useful and more likely to be used.

Model testing for boundary objects

Data reduction – factor analysis

Table 4 displays the bivariate correlations among the computed indices. The strongest correlates of behavioral intention to use climate change science, for both the pre-test and post-test, were usefulness and credibility. The strongest correlates of usefulness, for both the pre-test and post-test, were credibility and organizational barriers.

Regression Analysis of Usefulness and Behavioral Intention

Results from the OLS regression showed that both credibility and organizational barriers significantly predicted perceived usefulness both before and after the workshop (Table 5; Model 1). Next, we explored whether behavioral intention was explained by usefulness (Model 2), credibility (Model 3), and organizational barriers (Model 4). Each of these yielded a significant positive relationship, with usefulness for planning explaining nearly two-thirds, and credibility explaining one-third, of the variance in intention. Surprisingly, the positive relationship between organizational barriers and intention was the opposite of the negative relationship we had hypothesized.

Lastly, we ran a multiple regression that examined the relationship of all of the predictor variables on behavioral intention (Model 5). Usefulness for planning and credibility remained significant predictors of intention for the pre-test, and usefulness for planning was the only significant predictor of intention for the post-test. The direct effect of credibility on intention weakened in the final pre-test model and disappeared in the post-test model after adding the mediator usefulness. The direct effect of organizational barriers on intention was independently a significant predictor of usefulness (Model 4), but that effect also disappeared in the final models with the addition of the usefulness mediator. These findings suggest that the effect of credibility and organizational barriers on behavioral intention is largely mediated by perceived usefulness of the science.

Evaluation of the CCW boundary organization

Participants were asked during the post-test to rate their level of agreement with 19 statements related to the usefulness, credibility, and legitimacy of the CCWs as a whole (i.e. the *boundary organization*). Participants agreed that the CCWs were salient/useful overall, and it was encouraging that participants largely agreed that the CCWs made science more useful for management purposes. Many participants commented on the local saliency of the CCW, pointing out that "[the CCW brought] everyone up to date as far as climate change science goes, especially for the [northern Rocky Mountains], rather than just a global picture. It was more about our area of concern and interest… I wasn't aware of those types of data and projections …. [The CCW] added more precision" (Manager 1, Missoula).

The CCWs enhanced climate change science credibility by translating complex science and meeting science needs with data from multiple sources, and many participants commented that they learned during the CCW. One person said, although "there were some specific intricacies" that she "didn't fully understand," nevertheless she felt she had "learned something… [such as] increases in intensity of spring rainfall... and the visual 3D depiction of rain and snowfall" (Manager 6, Missoula). Nearly all participants commented that allowing participants to process the information in small group discussions was a valuable part of their CCW experience. One participant said, "we had a good discussion at our table concerning the uncertainty of making projections, as to what species will be where, [and] how to manage a forest in the future. I was able to talk about that with the folks, and maybe even firm up my opinion about how to deal with that" (Hydro 1, McCall). Participants disagreed with the statement that the presentations at the CCWs were too detailed, but it was often expressed that participants desired more time to reflect on the new information being presented.

Legitimacy was defined as the presentation of information and technology in a manner that is respectful of stakeholders' divergent values and beliefs, unbiased in content, and fair in its treatment of views and interest. Participants reported the highest level of agreement with the legitimacy questions. They felt comfortable to share openly, that diverse opinions were welcome, and that they were being heard. Participants felt that an important aspect of the CCWs was that they created a space for scientists, agency personnel, and interested stakeholders who otherwise would not have occasion to work together to engage in productive debate. Many participants commented on the two-way exchange of information; for example, one participant appreciated the forum's goal to "both to share information… and engage with people that are using it and get more feedback" (Manager/Planner 2, Missoula). The application of workshop best practices and careful consideration of science communication resulted in a positive evaluation of the CCW experience.

Discussion

We evaluated the effectiveness of boundary objects (i.e. workshop components) and a boundary organization (i.e. the overall workshops) for influencing workshop participants' attitudes towards the usefulness of climate change science in land management. We gained a greater understanding of boundary work constructs, organizational barriers, and intention to use climate change science for management decisions at various spatial and temporal scales, using multiple methods of inquiry.

The effectiveness of boundary objects

We found support for several of our hypotheses related to the boundary objects. Similar to the case study by Cutts *et al.* (2011), participant perceptions of the usefulness (H1a) and credibility (H1b) of climate change science significantly increased because of participating in the CCWs. Positive relationships were also observed between credibility and usefulness (H2), and between usefulness and intention to use climate change science in future work (H3). Further, we found that the influence of credibility and organizational barriers on behavioral intention was largely mediated by perceptions of usefulness (H5). Our data provided rich context about how participation in the CCW influenced (or did not influence) perceptions of salience/usefulness and credibility at different spatial scales. Prior to the CCWs, many participants indicated that climate change science was most useful for long-term land use planning and regional scale management decisions (e.g. forest plans), rather than fine-scale specific forest projects (e.g. plot-level thinning projects), and the CCW did not have a significant impact on this perception. Participant comfort with using climate change science at regional scales may be due, in part, to current agency guidance for using climate change science at that scale (Dillard, 2008; U.S. Department of Agriculture, 2010). However, interviews suggested other reasons about why participants may have favored the regional-scale climate change boundary objects.

Nearly all interviewees indicated a preference for the regional scale hydrologic modeling, where they were able to witness animation of projected changes in the rain/snow transition zones for the forests they manage. This hydrologic modeling was also consistently rated as more useful and credible than global and local-scale modeling on the surveys. The primary difference between the regional hydrologic modeling and the other types of modeling used during the CCW (i.e. regional vegetation shifts, wildland fire area burned, and stand-level vegetation simulations) was that it used direct, historical measures of climate in which projected changes in temperature were used to predict rain versus snow. This was more credible than the vegetation and fire modeling because it relied on a small number of simple variables that were easy to comprehend and had less uncertainty. This finding is consistent with other studies that have shown that natural resource managers believe simple and direct measures of climate (i.e. precipitation, temperature, and snowpack) as these measures are the most useful for their work (Klos *et al.*, In Press).

The visualization and animated aspects of the hydrologic modeling were captivating and powerful. They simplified, summarized, and made the information locally relevant to the CCW participants, consistent with other literature on climate change visualization (e.g. Al-Kodmany, 2002; Lipkus, 2007; O'Neill and Nicholson-Cole, 2009). The animated sequence allowed participants to focus their attention on climate change impacts within the forests they manage, consider those impacts against other important resources of the region (e.g. big game winter range and Canada lynx habitat), and then process the information in a deliberative small group discussion. The benefits of this approach were consistent with research that has shown that interactivity enhances visualization, notably when used in a carefully designed workshop setting that uses small breakout groups (Schroth *et al.*, 2011). Similarly, Cutts *et al.* (2011) highlighted the importance of Geographic Information Systems (GIS), maps, and scientist-guided discussions as being effective boundary objects. This dynamic engagement was not possible with the other types of boundary objects presented at the CCWs, so it is not possible to determine whether the greater credibility of regional hydrologic models was due solely to the visualization or the simplicity of the models. Thus, future research should compare the effect of visualizations from models differing in complexity and associated uncertainty to gain a better understanding of effects of visualization on perceptions of credibility and usefulness.

Beyond considerations of visualization and model complexity, there was also clear evidence of a scale mismatch between participant needs related to climate change science and perceptions of the credibility and usefulness of the climate change science we presented. For example, prior to the CCWs, interviewees expressed that climate change science was not useful because it addressed scales that were too broad for forest management, and they desired more local-scale information. After the CCWs, the scale mismatch existed in the opposite direction; although local-scale climate change science was presented, participants preferred the regional scale modeling. In post-CCW interviews, it was common to hear about challenges related to the uncertainty and assumptions associated with the local-scale vegetation modeling (e.g. the selected types of forest treatments, timing of the treatments, fire disturbances, and reestablishment rate), which people thought reduced its utility for management decisions. Sometimes the local-scale vegetation modeling was credible but not useful because it was accurate for a small parcel of land but did not capture variability in the larger landscape. Other times the information was described as not locally credible but still useful; the landscape variability was not captured (lacks credibility) but the model was still considered useful for exploring and comparing land management alternatives. The CCWs revealed a participant preference for boundary objects that provided coarse representations of climate change impacts, such as the hydrologic spatial model that illustrated relative shifts in rain/snow zones, rather than quantitative predictive boundary objects, such as the local-scale vegetation simulations. Many people expressed a desire for local-scale predictive modeling, but said that the complexity and uncertainty was too great to use it as a prescriptive management tool.

These findings related to scale suggest that tradeoffs existed between the usefulness and credibility of climate change modeling at different spatial scales. This is consistent with the findings of White *et al*. (2010) that trade-offs existed between boundary object variables (i.e. credibility decrease and usefulness increase) when workshop participants evaluated a complex system dynamics model. The CCWs were effective for helping to define the usefulness of climate change science at different scales and determining which scales were more useful, which is a desirable function of an effective boundary organization (Cash, 2001; Guston, 2001). As climate change science becomes increasingly more accurate and precise over time, future research should track perceptions of its credibility and salience at different spatial and temporal scales.

Organizational Barriers Overcome by Boundary Objects

Although nearly all CCW participants agreed that climate change science should be used in forest management, participants also strongly agreed that time, funding, and politics act as constraints for addressing climate change in their work. The interviews consistently indicated that agency personnel have a full plate of work expectations, and climate change was yet another responsibility on top of many other higher priority topics. These findings are consistent with other work regarding barriers to using current science in natural resource management (Archie *et al.*, 2012; Jantarasami *et al.*, 2010; Wright, 2010), where a large majority of respondents agreed that time and politics acted as barriers to using the “best available science” in management decisions.

Because of these consistent findings in the literature about organizational barriers, we initially hypothesized that higher levels of perceived organizational barriers (time, funding, and politics) would be associated with lower perceived usefulness of climate change science (H4a) and with lower intention to use climate change science in management decisions (H4b). However, neither hypothesis was supported by our findings. In fact, a positive relationship existed between organizational barriers and the usefulness and intention to use climate change science. This finding might be explained by feedback we received from CCW participants throughout the entire research process: no one has the time or ability to collect, interpret, and summarize the vast amount of climate change science available, which is why the CCW was desired as a mechanism to achieve those purposes. The pre-CCW interviews commonly demonstrated this need, and nearly all of the post-CCW interviews commented on how this need was met by the CCWs. This finding was also reflected in the post workshop questionnaire results, where nearly all participants agreed that, during the CCW, scientific information and results were translated for practical use. This overcame the barriers of time and funding that would be necessary to gather and synthesize climate change information independently. Alternatively, if the barriers are related to politics, more credible climate change science may be the solution to political barriers. Regardless, the positive relationship between organizational barriers and intention to use climate change science was perplexing and worthy of further investigation.

A hybrid boundary organization-object

Prior work has consistently identified the need for institutionalized boundary organizations (Cash, 2001; Guston, 2001; White, 2011; White *et al.*, 2010), with long-term relationships between actors from differing worlds. However, such institutions require high levels of investment and resources from all participants. There is often a need for short-term partnerships that provide rapid science delivery and deliberation between scientists and land managers/decision makers. Thus, we aimed to explore the effectiveness of a hybrid boundary organization-object positioned in the overlapping space of scientific research and natural resource management and decision-making. Further, it is also common to lack the necessary funding that would accommodate a long-term consistent relationship or institution. Thus, we explored how well the CCWs, representing a short-term organization, but also a knowledge transfer tool, could achieve the goals and purposes of a long-term institutional organization. Our findings suggest that the CCWs were effective for increasing salience, credibility, and legitimacy, and facilitated a multi-directional flow of information. Participant feedback expressed that the CCWs served the crucial roles of meeting agency desires for linking climate change science with information needs, translating the practical uses of the information, and creating opportunities for deliberation that would otherwise be unlikely between the diverse participants. Participants also agreed that the workshop encouraged the use of models and tools (i.e. boundary objects) for linking science and decision-making, and they considered the tools to have met their needs. These findings are consistent with literature specific to the necessary functions of a boundary organization (Buizer *et al.*, 2010; Cash, 2001; Guston, 2001; Miller, 2001). Participants clearly felt that the CCWs facilitated knowledge and information exchange among scientists, land managers, and decision-makers (H6).

Despite the positive response, there are limitations to conducting a one-day workshop, as opposed to establishing a long-term institution. A central finding of Cash *et al.* (2003) was that a long-term perspective and commitment to managing boundaries between scientists and decision-makers was more effective for linking knowledge to action. We acknowledge the generally slow impact of ideas on practice, and are curious whether participation in our one-day CCW provided enough time to process the workshop information and link it with day-to-day forest management practices. Participants only slightly agreed that there was adequate time to reflect on the new information, but many also stated that if the workshop had been longer than one day, participation would not have been possible given time constraints. This finding is not altogether surprising because agency personnel consistently report that time is a major limiting factor for collecting, reflecting on, and using current science (e.g. Wright, 2010). To understand the impact of CCWs on actual forest management practices, future research should focus on the effect of short-term workshops designed for rapid science delivery on actual subsequent forest management decisions.

Conclusions

Our intent when designing this study was to address disconnects between the supply of academic research related to climate change impacts and the needs of forest managers for regional- and local-scale information pertinent for decisions. Our findings suggest that the CCWs were effective for the rapid delivery of climate change science in a setting that capitalized on the use of visualization and interactive participation. Often scientists struggle to get useful information out to land managers on-the-ground and are not able to conduct comprehensive long-term collaborative partnerships. We found that a one-day workshop, when carefully designed, can accomplish a great deal using a hybrid boundary organization-object framework. Perceptions of the usefulness and credibility of climate change science increased, and both were significant predictors of intention to use climate change science in land management decisions.

We designed the CCWs to serve as research-management partnerships aimed at integrating climate change science and management. The CCW participants reflected that, overall, the CCWs were salient, credible, legitimate, and considered to be time well spent. The need for ongoing research-management partnerships that synthesize and translate climate change science, such as the CCWs, is imperative in the face of increasing organizational barriers that constrain agency specialists from adequately addressing climate change in natural resource management decisions.

This study represents a unique and rigorous empirical evaluation of boundary objects and hybrid boundary object-organizations. The use of multiple methods of inquiry revealed the primary importance of scale, model complexity, uncertainty, and visualization when designing, implementing, and evaluating climate change boundary objects. The visualization and animated aspects of the boundary objects were important to focus attention on climate change impacts within the geographic areas that participants manage. Our findings suggest that boundary objects that use direct measures of climate (i.e. temperature and precipitation) at a regional scale are considered more useful and credible than boundary objects that are more complex, use indirect measures, and estimate local-scale climate impacts within ecological systems.

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Tables

Table 5.1. Pre-test, post-test, and change of perceptions of climate change science credibility.

		Pre-test			Post-test				
Items*	*N*	Pre-test *mean*	*SE*	Factor loading	Post-test *mean*	*SE*	Factor loading	*Mean* Change	Paired T-test (*p*)
Global and regional climate change science is credible.	60	2.0	0.1	0.81	2.1	0.1	0.74	0.2	0.13
Local (forest stand-level) climate change science is credible.	52	0.9	0.2	0.77	1.2	0.2	0.61	0.3	0.11
Historical data and calculations used in climate change science are credible.	56	1.5	0.2	0.82	2.1	0.1	0.67	0.6	**<0.01**
Projected/modeled future data and calculations used in climate change science are credible.	56	1.0	0.2	0.87	1.6	0.1	0.77	0.6	**<0.01**
I consider science about climate change impacts to be defensible when a decision is challenged or appealed.	55	1.1	0.2	0.89	1.5	0.1	0.71	0.4	**0.03**
FACTOR mean				1.2 (0.1)		0.1	1.7	0.5	**<0.01**
Cronbach's alpha				0.9			0.7		
Eigenvalue				3.5			2.5		
% Variance explained				69.3			49.0		

* Scale values -3 (strongly disagree) to 3 (strongly agree)

Table 5.2. Pre-test, post-test, and change of perceptions of the usefulness of, and intention to use, climate change science

	Pre-test					Post-test					
Items*	*N*	Pre *Mean*	*SE*	Factor Loadings Planning	Factor Loadings Models	Post *Mean*	*SE*	Factor loadings Planning	Factor loadings Models	*Mean* Change	Paired T-test (*p*)
Climate change science is useful in my work.	61	2.0	0.1	0.81	-0.01	2.1	0.1	0.97	-0.22	0.1	0.33
Climate change science is useful in long-term land use planning.	58	2.3	0.1	0.81	0.16	2.4	0.1	0.82	0.20	0.2	0.16
Climate change science is useful for specific management projects.	60	1.5	0.2	0.93	-0.10	1.7	0.1	0.74	0.24	0.3	0.04
Models that simulate future vegetation scenarios are useful in land management.	58	1.6	0.1	-0.03	0.97	1.5	0.1	0.14	0.14	-0.1	0.51
Models that simulate future precipitation patterns are useful in land management.	59	1.5	0.2	0.04	0.94	1.7	0.1	-0.07	-0.07	0.2	0.29
FACTOR mean				1.9 (0.01)	1.6 (.01)			2.1 (.01)	1.6 (.01)	0.2	
Cronbach's alpha				0.8	0.9			0.8	0.8		
Eigenvalue				2.8	1.3			2.9	1.1		
% Variance explained				55.2	26.1			57.9	22.1		
The global climate change information is useful for land management (modeling and emission scenario information).						1.4	0.1				
The regional climate and water research is useful for land management.						2.2	0.1				
The regional vegetation and fire research is useful for land management.						2.2	0.1				
The local-scale forest vegetation and climate simulations are useful for land management.						1.9	0.1				
I plan to use climate change science in future work that I do.	61	2.0	0.1			1.9	0.1				0.56
I plan to use global climate change science in future work that I do.	58					1.1	0.1				
I plan to use the regional climate and precipitation research in future work that I do.	61					2.0	0.1				
I plan to use the regional vegetation and fire research in future work that I do.	58					1.7	0.1				
I plan to use the local-scale forest vegetation and climate simulations in future work that I do.	55					1.4	0.1				

* Scale values -3 to 3

Table 5.3. Pre-test perceptions of organizational barriers.

Items*	*N*	*Mean*	*SE*	Factor loading
Funding is a constraint for addressing climate change in my work.	60	1.2	0.2	0.87
Time is a constraint for addressing climate change in my work.	59	1.5	0.2	0.88
The politics of climate change are a constraint for using the science in my work.	59	0.5	0.2	0.73
FACTOR mean	61			1.1 (0.2)
Cronbach's alpha				0.9
Eigenvalue				3.5
% Variance explained				69.3

* Scale values -3 to 3

Table 5.4. Correlation matrix (Pearson's r) for the pre-test (below the diagonal) and post-test (above the diagonal) factors used in the multiple regressions.

Factors	1.	2.	3.	4.	5.	Mean	SE
1. Behavioral Intention	**1.00**	.81**	.35**	.55**	.35**	1.63	0.12
2. Usefulness	.79**	**1.00**	.38**	.61**	.54**	2.07	0.09
3. Usefulness of Models	.38**	.31**	**1.00**	.38**	0.11	1.58	0.11
4. Credibility	.55**	.47**	.55**	**1.00**	0.22	1.69	0.09
5. Organizational Barriers	.48**	.49**	.29*	0.24	**1.00**	1.07	0.17
Mean	1.98	1.89	1.58	1.24	1.07		
SE	0.13	0.12	0.14	0.13	0.17		

*Correlation is significant at the 0.05 level, **Correlation is significant at the 0.01 level

Note: The pre-test value for organizational barriers was used for correlations during both the pre-test and post-test (it was only measured during the pre-test).

Table 5.5. Linear regression results for usefulness of climate change science (pre-test and post-test).

	Pre-test				Post-test			
	β	*t*	*Adj. R^2*	*F*	*β*	*t*	*Adj. R^2*	*F*
DV: Usefulness (in general)								
Model 1:			0.32	**10.27****			0.54	**24.44****
Usefulness of Models	-0.01	-0.08			0.16	1.65		
Credibility	0.38	**2.96****			0.46	**4.74****		
Organizational Barriers	0.39	**3.43****			0.42	**4.63****		
DV: Behavioral Intention								
Model 2:			0.63	**101.10****			0.65	**114.04****
Usefulness	0.80	**10.10****			0.81	**10.70****		
Model 3:			0.29	**25.64****			0.29	**25.81****
Credibility	0.55	**5.06****			0.55	**5.08****		
Model 4:			0.22	**17.86****			0.11	**8.11****
Organizational Barriers	0.48	**4.23****			0.35	**2.85****		
Model 5:			0.66	**29.18****			0.65	**28.88****
Usefulness	0.63	**6.60****			0.82	**7.11****		
Credibility	0.21	**2.11***			0.06	0.63		
Organizational Barriers	0.12	1.33			-0.11	-1.20		
Usefulness of Models	0.04	0.42			0.03	0.35		

* Significant at the $P < .05$ level, ** Significant at the $P < .01$ level. $\alpha = .05$

Figures

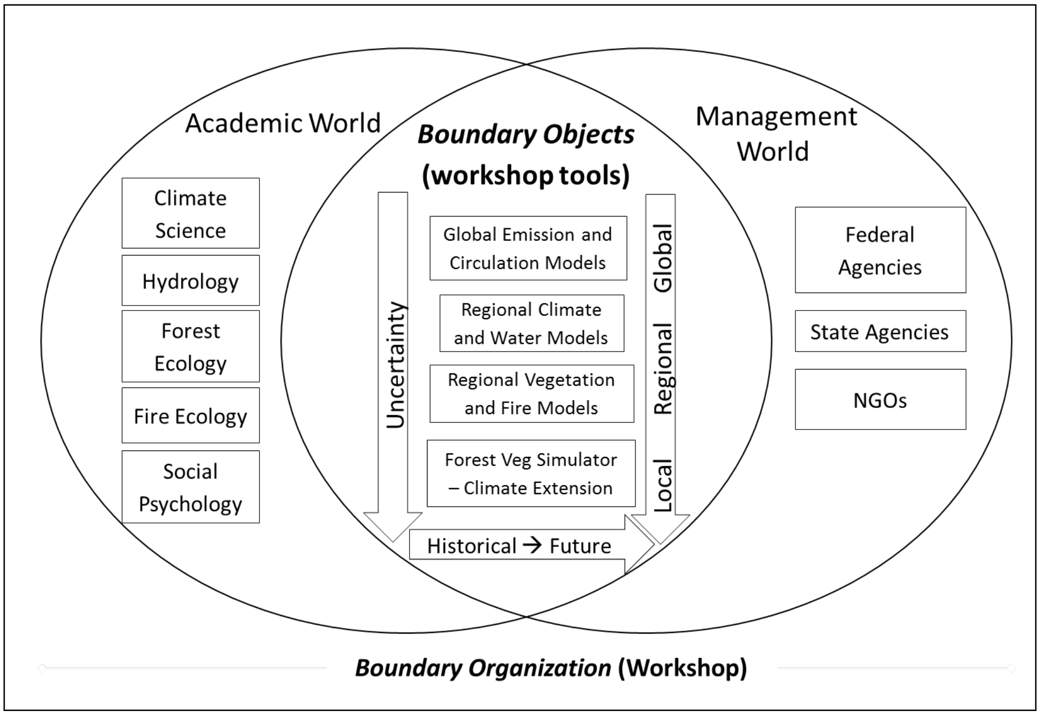

Figure 5.1. Conceptual diagram of the climate change workshops (CCWs), boundary organization, that linked academic and management worlds. The boxes on the left, academic world, are the disciplines represented by our interdisciplinary research team. The boxes on the right in the management world represent the diversity of stakeholders present at the CCWs. The boxes in the center represent the CCW tools that were evaluated as boundary objects. The large arrows show that the boundary objects spanned global, regional, and local spatial scales, historical and future temporal scales, and that uncertainty was present at all scales and compounded when transitioning from global to local and historical to future.

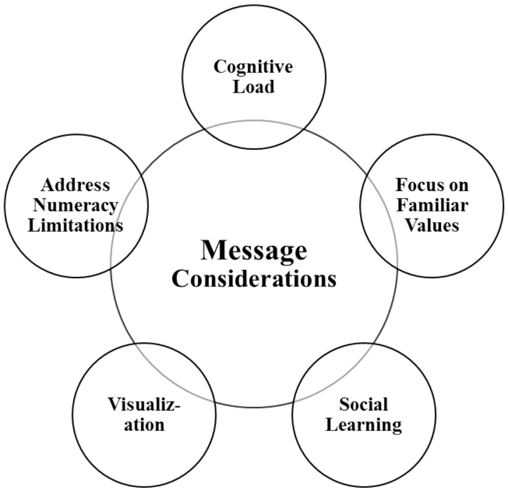

Figure 5.2. Climate change message considerations for the workshops.

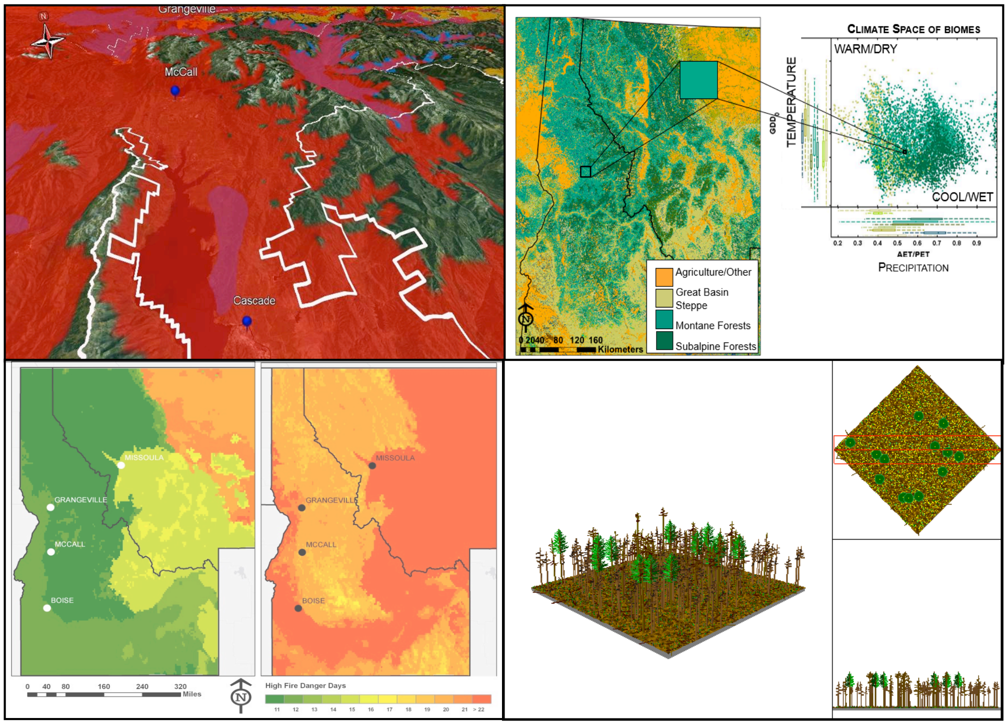

Figure 5.3. Example workshop visualization: a) changes in areas where winter is now (dark red) and will be (light red) dominated by rain snow mix overlaid on topography; this is the Bitterroot valley and surrounding mountains south of Missoula with National Forest boundaries (white) shown with current elk and lynx habitat, b) visualizing existing forest biomes and their climate "space", c) changes to the number of high fire danger days currently (left) and by 2050s (right) for Idaho and western Montana, and d) a stand of trees viewed from several different angles, all as projected using the Climate-Forest Vegetation Simulator (Climate-FVS) that enables managers to explore implications of forest growth and mortality (e.g. from cutting, insects and disease). These and other visualizations we used are available online: http://web.cals.uidaho.edu/northernrockies/workshops/download-workshop-materials/

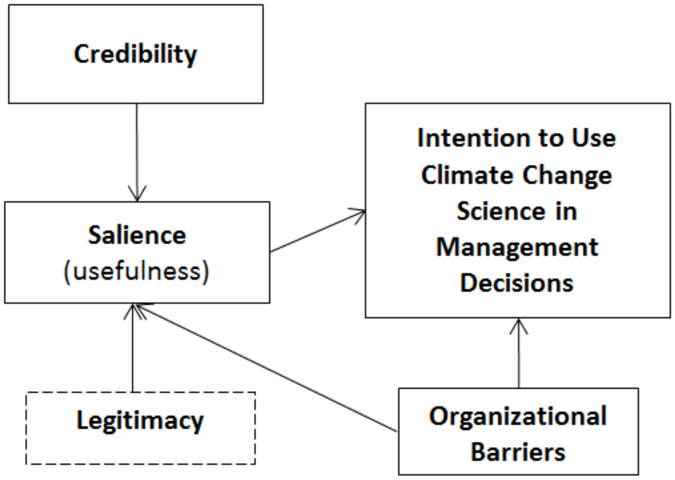

Figure 5.4. Integrated model of boundary variables, organizational barriers, and the intention to use climate change research in land management decisions. The dotted line indicates that legitimacy was only measured for the CCW boundary organization (not the boundary objects).

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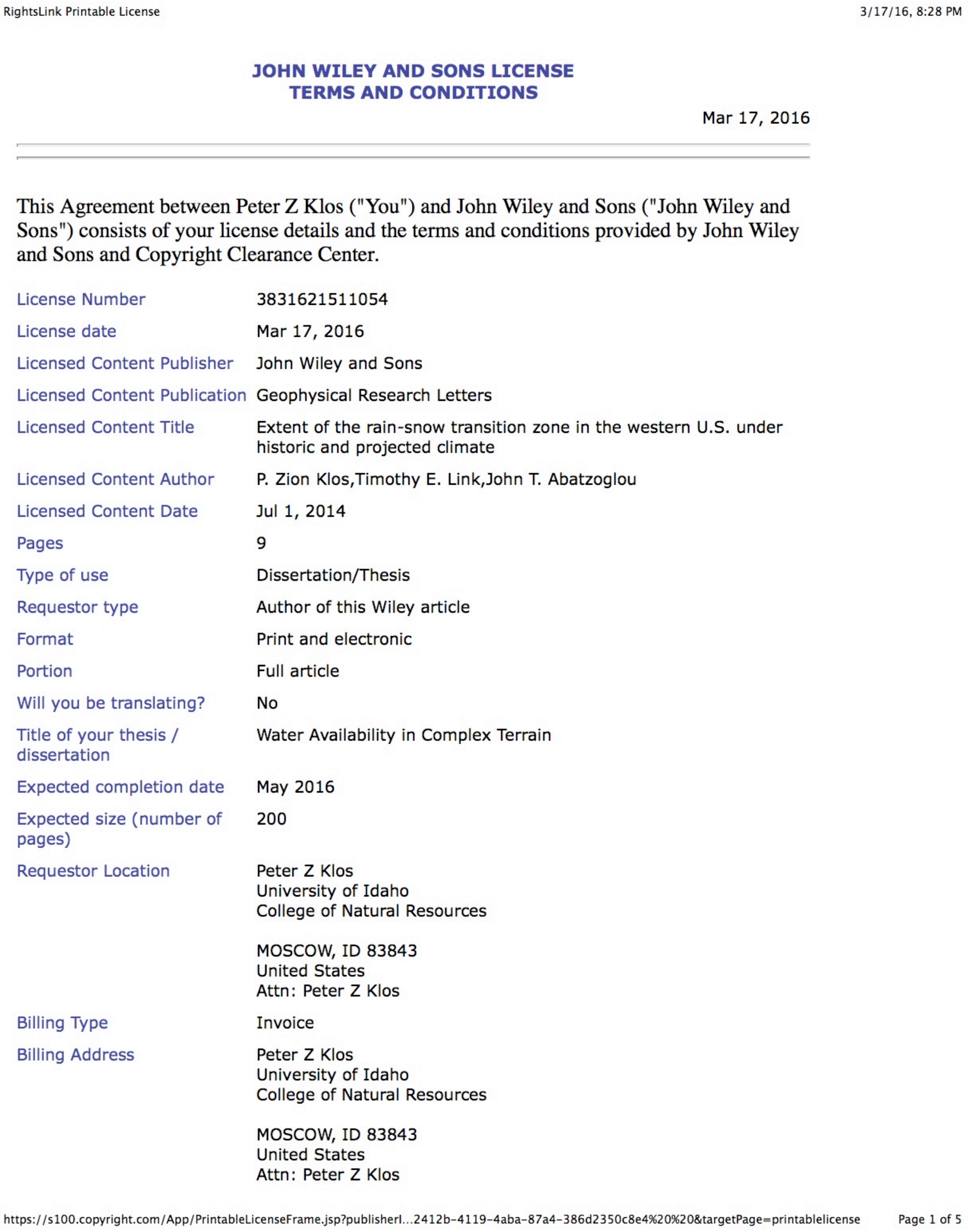

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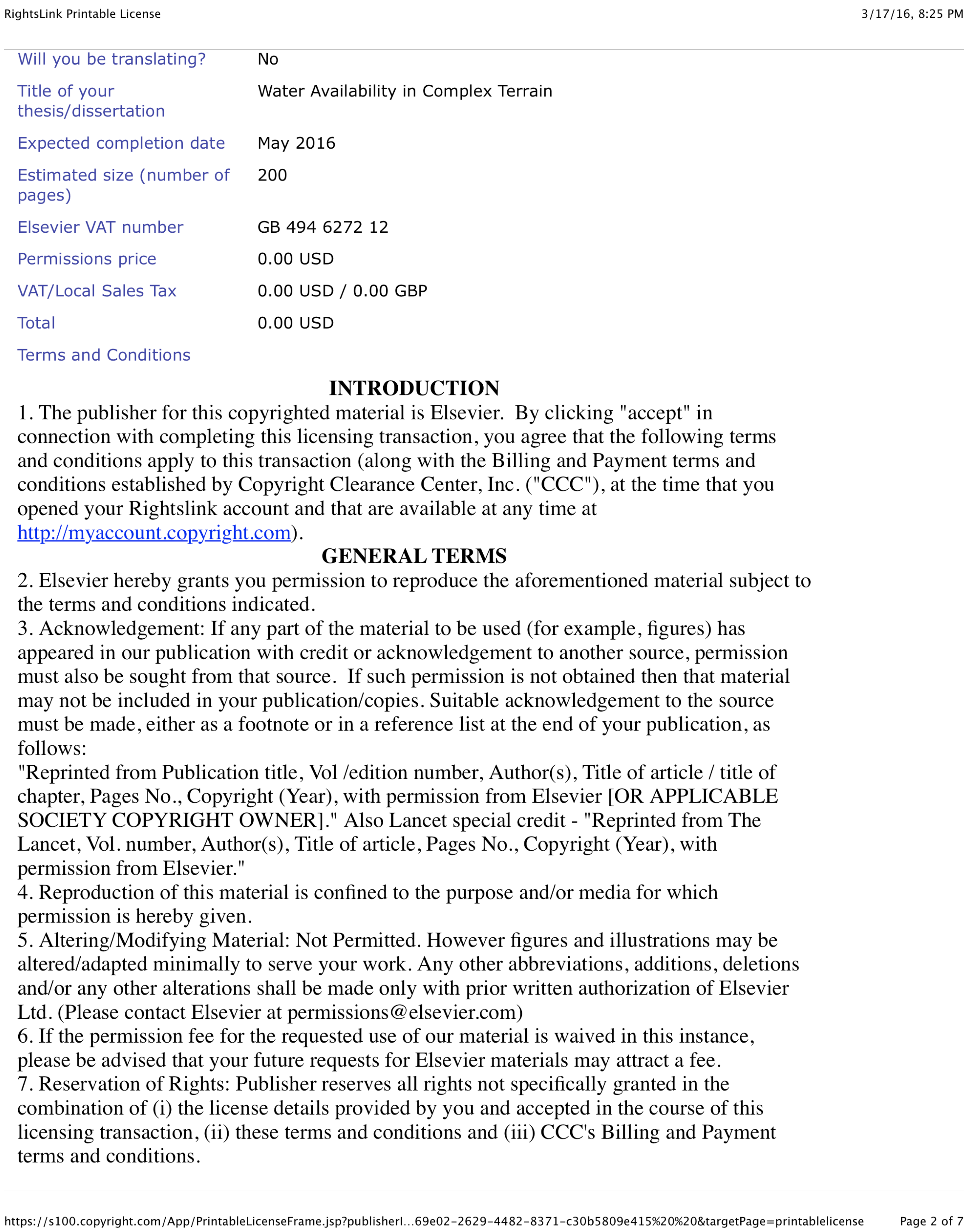

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