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Climate science information needs among natural resource decision-makers in the Northwest US

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ABSTRACT

Managing water resources, air quality, forests, rangelands and agricultural systems in the context of climate change requires a new level of integrated knowledge. In order to articulate a role for university-based research teams as providers of climate services, this paper analyzes environmental change concerns and expectations about climate models among natural resources decision-makers in the Northwest US. Data were collected during a series of workshops organized by researchers from BioEarth, a regional earth systems modeling initiative. Eighty-three stakeholders from industry, government agencies and non-governmental organizations engaged with a team of academic researchers developing integrated biophysical and economic climate modeling tools. Analysis of transcripts of workshop discussions, surveys, and questionnaires reveals diverse attitudes among stakeholders about: 1) preferred modes of engaging in climate science research, 2) specific concerns and questions about climate change impacts, and 3) the most relevant and usable scope and scale of climate change impacts projections. Diverse concerns and information needs among natural resource decision-makers highlight the need for research teams to define clear and precise goals for stakeholder engagement. Utilizing the skills of research team members who have communication and extension expertise is pivotally important. We suggest impactful opportunities for research teams and natural resource decision-makers to interface and learn from one another. Effective approaches include structuring group discussions to identify gaps in existing climate change impacts information, explicitly considering changing policies, technologies and management practices, and exploring possible unintended consequences of decisions.

Practical Implications

The impacts of climate change are currently felt in managed and natural systems throughout the Northwest US. Questions about specific impacts, system feedbacks, and opportunities for adaptation and mitigation actions are highly complex. Scientific understanding of these issues continues to evolve. The need for relevant climate services information that is accessible to natural resource managers focused on water resources, air quality, forests, rangelands and agricultural systems is growing. Regional-scale information is particularly valuable because it is at this scale that many specific environmental risks and opportunities for action exist.

Within climate information initiatives, stakeholders are generally considered to be those individuals and organizations that have the interest and ability to use climate science information in their decision-making (Cash and Buizer, 2005; McNie, 2007; Hegger et al., 2012). The research initiative presented in this paper considers decision-makers who focus on water resources, atmospheric issues, forests and agricultural systems to be key stakeholders. Potential participatory roles for stakeholders within climate research are varied and can include: identifying research questions, sharing values, preferences, expectations and perceptions of risk, providing quantitative data or local expertise, commenting on research concepts, drafts and results, learning from the research process, and

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integrating research findings into a decision-making processes (BÌckstrand, 2003; Bucchi and Neresini, 2008). There is widespread agreement that *early* stakeholder engagement in research is more likely to ensure that problem definition and approaches to collecting data and communicating research findings are aligned with stakeholders' needs (Rowe and Frewer, 2005; Reed et al., 2009; McNie, 2012). However, specific protocols for academic modeling teams to engage with stakeholders and produce actionable model outputs have been subject to limited research and are not yet well defined (Reed et al., 2009; Prell et al., 2009; McNie, 2012; Weaver et al., 2013).

Natural resource decision-makers are a heterogeneous group with different interests, concerns and motivations; they hold a range of perspectives about the value and applicability of climate research to their work (Feldman and Ingram, 2009). Most natural resource decision-makers would agree that monitoring, or collecting empirical data about current conditions, is a source of credible information about the state of environmental systems. For example, scientific monitoring assessments and inventories are widely relied upon to document the environmental effects of federal agency actions, such as Environmental Impact Statements required under the US National Environmental Policy Act (Linkov et al., 2006).

Unlike environmental monitoring and other forms of field and laboratory research, modeling is often not well understood by decision-makers (Hartmann et al., 2002; Frigg and Hartmann, 2012; Akerlof et al., 2012). Models are, by definition, simplifications of real-world systems and processes (Frigg and Hartmann, 2012). Models enable projections about the future based on an understanding of the underlying processes at work, current information, and an assessment of likely trends (Allen et al., 2015). Some decision-makers may be predisposed to view climate change impacts modeling with suspicion because model outputs might suggest a change in practice that could be inconvenient or expensive (Akerlof et al., 2012). Or in many cases, skepticism about model outputs is rooted in the observation that weather forecasts and economic projections are ''frequently wrong'', illustrating a lack of experience with models and limited understanding about uncertainty and how model projections are generated and evaluated (Akerlof et al., 2012). Challenges associated with applying outputs from climate model simulations to decisions arise for the following reasons: 1) model results are typically stored in formats that require familiarity with computer programming, 2) outputs may be formidably large to download and analyze, and 3) outputs are often not refined to reflect conditions specific to a location of interest for individual users (Allen et al., 2015). To maximize the usability of environmental models for decision-making, effort is needed to assess decision-makers' information needs and to tailor communication strategies to be compatible with their expertise (Dilling and Berggren, 2015; Archie et al., 2012). When natural resource decision makers have sophisticated understanding of how models are developed they can better ask questions about the relevance of a model for a particular decision (Liu et al., 2008; Hallegatte, 2009; Schmolke et al., 2010).

BioEarth is a university-based integrated climate change impact modeling effort attempting to integrate economic and biophysical models to provide more usable climate change impacts information for decision-makers concerned with natural resource management regulations and policies. Six stakeholder workshops were convened for researchers to learn about concerns and information needs among natural resource decision-makers in the Northwest region of the United States. Analysis of workshop transcripts, surveys and questionnaires led to the identification of four themes related to key environmental, social and economic challenges facing the Northwest now and in the future: 1) climate change will exacerbate many existing environmental issues; 2) land use change and development are key issues facing the region; 3) scenarios of the region's future should explicitly analyze possible impacts of political and economic changes; and, 4) impacts of decisions across jurisdictions and management sectors must be considered.

Input from natural resource decision-makers played a central role in determining the direction of BioEarth model development efforts. Some of the information needs defined by stakeholders were beyond the scope of possibility for this specific research effort. However, researchers came to understand pressing environmental change questions from the point of view of regional natural resource decision-makers and gained an appreciation for the institutional context in which decision-making occurs and the constraints that natural resource decision-makers face in incorporating climate science information in management and policy decisions. Based on feedback on the BioEarth workshops shared by stakeholders, we found that research team members with a background in communication and extension performed a central role in facilitating the sharing of information between researchers and stakeholders. Informed by stakeholder input during and after workshops, we make the following recommendations for regional climate change impacts modeling teams: 1) structure discussions with regional stakeholders to identify specific information gaps and temporal and spatial scales of most interest, 2) incorporate policy changes, emerging technologies and management practices into scenarios that are modeled; 3) consider the impacts of projected land use change in combination with projected climate change impacts 4) compare the modeled outcomes of current best management practices vs. what are understood to be ''worst practices''; and 5) show straw man model outputs to stakeholders to foster discussion about assumptions embedded in the model and sources of uncertainty. These lessons learned about climate science information needs and stakeholder preferences for how model outputs are communicated are broadly relevant to the growing field of regional climate change impacts research efforts.

1. Introduction

The notion of a gap between research and decision-making has emerged as a central trope in climate science communication literature. Most potential users of climate science research are either unaware of available research, or unable to access and interpret relevant climate science (McNie, 2012; Lemos et al., 2012; Weaver et al., 2013). There are missed opportunities to link the supply of scientific information with users' demands, and hence missed opportunities for science to inform policy and decision-making (Sarewitz and Pielke, 2007; McNie, 2012).

Within the climate science research community, there is a long lineage of calls for usable science from funding agencies, stakeholder groups, and research institutions. In 1999, the US National Research Council promoted a new model of research, led by users' concerns and key questions. This was in response to growing understanding that local knowledge and practices are not only frequent *sources* of environmental concerns but are also *resources* for addressing sustainability challenges (Miller et al., 2014). Building on the history of applied research in the US cooperative extension service, a resurgence of engaged research includes focusing on place-based science, collaborating with local communities to define research questions and developing tools that link knowledge and action (US National Research Council, 1999, 2001). Providing effective climate services requires active communication and exchange of information among information producers, translators, and user communities (Dilling and Berggren, 2015).

Although the need for practical knowledge of how to foster more intensive collaboration among academic scientists and decision-makers is increasingly acknowledged, best practices for stakeholder engagement are difficult to define because local concerns and approaches to management are highly variable (Jantarasami et al., 2010; McNie, 2012; Kirchhoff et al., 2013). Researchers must seek to understand natural resource decision-makers' climate science information needs in more depth and detail (Kasperson, 2011; Kirchhoff et al., 2013; Dilling and Berggren 2015; Miller et al., 2014).

In order for climate science research conducted at academic institutions to be usable for decision-makers, those decision-makers must be engaged early in often in the research process. Stakeholders' decision-making contexts and constraints must be made more transparent to researchers and research organizations (Kasperson, 2011; Dilling and Berggren, 2015). The objective of this research is to identify dominant environmental concerns, questions about projected climate change impacts, and information needs among natural resource management decision-makers in the Northwest US through a case study assessment of stakeholder workshops held as part of the BioEarth research initiative. Through analysis of workshop discussion sessions and surveys completed by participating stakeholders we address the following research questions: 1) how do information needs vary among stakeholders with different professional roles and natural resource systems of focus? and, 2) which approaches to research communication and model outputs are deemed by stakeholders to be most relevant to their natural resource management decisions? A core motivation for this research was the observation that natural resource managers have diverse levels of familiarity with environmental models and their information needs are often not well served by existing regional climate change impacts models (McNie, 2012; Kirchhoff et al., 2013).

This research analyzes dominant environmental concerns, questions and information needs among decision-makers working in different sectors. The unique backgrounds, responsibilities, geographic areas, and areas of expertise of stakeholders are considered with respect to the kinds of climate science information they deem usable and their assessments of which temporal and spatial scales are of interest. Based on insights from stakeholders, we explore opportunities to enhance the usability of regional climate impacts models for non-academic decision-makers. We document diverse concerns about environmental change and diverse perceptions of what constitutes usable climate science information among natural resource decision-makers in the Northwest region of the United States. Finally, we consider how university-based climate modeling teams can best utilize resources to design and implement efficient and impactful stakeholder engagement processes.

2. Background on the BioEarth research project

BioEarth, a transdisciplinary integrated modeling research initiative, is an example of a project that works toward bridging the gap between science and decision-making about natural resource management regulations and policies (Adam et al., 2014). The BioEarth project was funded in 2011 by US Department of Agriculture, National Institute of Food and Agriculture (NIFA) (proposal number 2011-01177). The research plan focused on working closely with stakeholders to produce results that are relevant to the needs of agriculture and forestry decision-makers. The central aim of BioEarth was to develop a model that enhances understanding of how climate change will impact cultivated cropping systems, rangelands and forest ecosystems and provides insight about the effects of resource management decisions on earth system processes. The research investigates climatic and anthropogenic interactions with nutrient cycling, water resources and air quality in the US Northwest region, focusing on the Columbia River basin (Adam et al., 2014). BioEarth is among a new generation of large environmental change research projects designed to be transdisciplinary in nature, with decision-makers who were external to the research team directly engaged in co-producing scientific knowledge (Godin and Gingras, 2000; Cummings and Kiesler, 2005).

The interdisciplinary BioEarth research team comprises individuals from atmospheric sciences, biogeochemistry, agricultural sciences, hydrology, aquatic chemistry, economics and environmental communication. A communication working group, involving researchers with both scholarly and practical expertise in communication and extension, collaborated to develop mechanisms for interaction between model developers and stakeholders. This effort included coordinating a series of stakeholder workshops, each focused on a different sector of natural resource decision-making (Allen et al., 2013). Previous research conducted by the BioEarth communication working group looked at how academic climate modelers perceive the role of non-academic stakeholders in model development and the role of models in natural resource management decisions (Allen et al., 2013).

3. Methods

3.1. Format of stakeholder workshops

In order for the BioEarth research team to learn from regional natural resource decision-makers and work toward developing actionable climate change impacts model outputs, six BioEarth stakeholder engagement workshops were convened in different locations across Washington State between February 2013 and March 2015. Each workshop focused on a specific natural resource management issue: 1) water quality, 2) water supply, 3) air quality, 4) rangeland management, 5) forest management, and 6) carbon and nitrogen management. Workshops consisted of an introduction to the BioEarth modeling approach followed by discussion about participants' priority environmental concerns, information needs related to climate change, and specific future regional modeling scenarios that would be impactful for their work. Complementing the discussion, multiple-choice questions were posed using Turning Point "clicker" audience response technology, handheld devices that enable participants to anonymously answer questions and see the answers from other participants displayed instantaneously. This process provided participants with a sense of the range of opinions in the room and catalyzed discussion. An average of 17 stakeholder participants and nine BioEarth research team members attended each workshop.

3.2. Stakeholder selection process

Stakeholder analysis is generally understood to be the process of identifying individuals or groups that are likely to affect or be affected by a decision and classifying them according to their relationship to the issue or decision at hand (Freeman, 1984; Reed et al., 2009). A broad range of methods have been developed and adapted for stakeholder analysis in disciplines including business, conflict resolution, natural resource management and others (Reed et al., 2009). There is, however, only limited information about which approaches to stakeholder analysis are most equitable, appropriate and effective for unique situations (Reed et al., 2009; Weaver et al., 2013). Social network analysis, snowball sampling, focus groups, interviews and surveys are examples of widely used tools for stakeholder analysis that may be used individually or in combination for both qualitative and quantitative stakeholder analysis (Prell et al., 2009; Reed et al., 2009).

BioEarth stakeholders were identified through a snowball sampling process that began with BioEarth research team members listing individuals and organizations that engage with natural resource management issues on a regular basis. Some individuals were identified based on research team members' existing professional contacts, while others were identified through organizational and agency websites. Invitations to participate in BioEarth workshops were sent to those individuals, who were in turn asked to refer other potential participants. A total of 328 individuals were invited to six BioEarth workshops, and 25% of invitees, 83 stakeholders, ultimately participated in workshops. Some stakeholders participated in more than one workshop, so there were a total of 100 instances of stakeholder participation. For individuals who participated in two separate workshops, only their second pre- and post- workshop questionnaires were analyzed. Individuals' views about sector-specific information needs and concerns were assessed for each workshop instance. Individuals' perspectives about trusted sources of information and how effectively researchers communicated were found to be consistent over time. The percentage of those invited that participated was consistent for all sectors (academia, tribal, federal, state or local government agency, industry or non-governmental organization). Table 1 describes the professional roles and employment sectors of participating stakeholders.

Table 1
Professional roles of workshop participants.

Professional role	Sector	Number attending
Public resource manager Involved in decisions about management of public lands, water resources and/or air quality. May play a role in developing site-specific management plans or enforcing regulations related to public land and resources.	Government NGO	33 1
Private resource manager Concerned with decisions about privately owned land and resources. May be a landowner, lessee (farmer or forester) or consultant advising about private land management decisions.	Industry	10
Researcher Conducts scientific research and/or analyzes data about regional environmental and natural resource issues. Work is centered on developing knowledge of systems, not directly involved in developing policies or policy implementation and evaluation.	Academia Government Industry NGO	6 7 3 5
Educator/communicator Work is centered on sharing knowledge with various publics. Focused on issue awareness and education as opposed to direct involvement in resource management decisions. Includes traditional university extension work.	Academia NGO	7 1
Policy advocate Represents an interest group (industry, community or environmental concern) in government policy decision-making processes.	NGO Industry	9 1
Total		83

3.3. Data collection and analysis

After each workshop, the BioEarth communication working group conducted thematic content analysis of stakeholders' information needs and stakeholders' reflections about participation in a climate science communication and engagement processes. Qualitative and quantitative data about perceptions held by natural resource decision-makers and their information needs were drawn from: 1) transcripts of workshop discussions, 2) pre-workshop surveys, 3) responses to multiple-choice questions posed during workshops, and 4) post-workshop surveys. Seventy-six of the 83 workshop participants completed pre-workshop surveys, and 51 completed post-workshop evaluation surveys. Pre and post workshop survey response rates were consistent across all six thematically arranged workshops (approximately a 90% response rate for pre workshop surveys and a 60% response rate for post workshop surveys). Pre and post workshop surveys covered expectations of modeling research and preferences related to model communication (see Supplemental materials for complete surveys). Workshop clicker questions and open-ended discussion questions were designed to gather information on specific environmental change concerns, science questions and information needs.

Researchers used QSR International's NVivo 10 qualitative data analysis software to code workshop notes and written survey responses. Two researchers carried out coding simultaneously, one internal to the project, and one who was external to the project and not involved beyond analyzing the documents. Codes developed by each researcher were compared, refined and clustered into thematic categories for analysis and quantitative assessment (e.g. classifying concerns raised by participating stakeholders based on priority rankings defined by participants).

4. Results and discussion

4.1. Priority concerns related to environmental and socioeconomic change

At each workshop, multiple-choice clicker questions and open-ended discussion questions were posed to investigate the specific issues that natural resource decision-makers were most concerned about. The top five highly ranked concerns about environmental change and emerging threats to natural resources identified by participants at each workshop are outlined in Table 2. Coding of workshop discussion transcripts led to the identification of over 100 environmental change concerns that were discussed, which were ranked based how highly they were prioritized by participants in clicker questions and in their discussion comments at each workshop. Table 2 provides a summary of the environmental change issues that rose to the forefront of discussions at each workshop.

Integrated analysis of data from all the workshops led to identification of the following four themes concerning key environmental, social and economic challenges facing the Northwest US now and in the future: 1) climate change will exacerbate many existing environmental issues; 2) land use change and development are key issues facing the region; 3) scenarios of the region's future should explicitly analyze possible impacts of political and economic changes; and, 4) impacts of decisions across jurisdictions and management sectors must be considered. Each of these themes is explained in detail below.

4.1.1. Climate change will exacerbate many existing environmental issues

Across all six thematically arranged workshops and across all categories of stakeholders' professional roles we found a widespread perception that anthropogenic climate change in the Northwest US is already occurring, will intensify in the coming century and will exacerbate existing environmental challenges in the region. At the same time that climate change information suggests the need for consideration of adaptation and mitigation decisions, management for climate change is often difficult in the context of existing institutional mandates. The degree to which workshop

Table 2
Top 5 highly ranked concerns at each BioEarth stakeholder workshop.

Workshop focus	Concerns discussed by participating stakeholders, listed according to overall priority ranking
Water quality	1. Changes in amount and seasonality of precipitation, timing of snowmelt runoff leading to reductions in water quality 2. Erosion and sediment in waterways linked to forest management practices and changing riparian zone protection policies 3. Nitrogen and phosphorous loading; harmful algal blooms and impacts to drinking water 4. Impacts of water temperature change on native species (salmonid populations) 5. Urban runoff, linked to ongoing development and impervious surfaces
Water supply	1. Reduced snowpack and earlier snowmelt leading to reduction in summer instream flows 2. Increasing out-of-stream demand for water linked to development and changing land use 3. Increasing irrigation efficiency and concerns related to "water spreading" and increased consumptive use 4. Management practices that do not jointly manage surface water and groundwater, conflicts between water management jurisdictions 5. Increased frequency of drought
Air quality	1. Nitrogen deposition impacts on ecosystem function, and cropland, forest and rangeland productivity 2. Visibility and respiratory health issues from agricultural dust linked to tillage and land management practices 3. Impacts of prescribed burning on air quality and fire cycle 4. Transport of pollutants from Asia 5. Odor impacts from dairy industry
Rangeland management	1. Soil moisture (timing and volume of water storage), increasing frequency of multi-year droughts and extreme precipitation events 2. Erosion due to changing seasonality and amount of precipitation, impacts of decreasing air and water quality (also linked to riparian zone protection policies) 3. Ranges of invasive plant species (cheat grass and medusa head), juniper and pinion encroachment as it impacts forage quality and overall ecosystem function 4. Intensifying wildfire frequency and severity 5. Wildlife-livestock interactions
Forest management	1. Length of summer dry period and frequency and intensity of droughts, particularly in the inland areas of the Northwest (east of the Cascade Mountains) 2. Changes in wildfire frequency and severity and associated damage to soils 3. Pest and disease pressure; feedbacks between drought, fire, insects and disease 4. Climate change and management practices as they impact genetic diversity of forests and invasive species 5. Potential for increasing frequency and severity of ice and wind storms
Nitrogen and carbon management	1. Contribution of nitrous oxide and carbon dioxide emissions to greenhouse effect 2. Nitrogen runoff and leaching from synthetic fertilizer and organic amendments applied to crops 3. NO_x contribution to air quality issues, nitrogen deposition as it impacts forests and water quality 4. Carbon storage potential of croplands and rangelands—concerns about developing policies to support management practices that enhance carbon storage 5. Impacts of wildfire on carbon storage potential of forests

participants make management decisions that explicitly consider climate change depends upon the sector they work in and their professional role.

Natural resource decision-makers face several limitations to explicitly incorporating climate change projections into resource management planning. For example, a representative of a federal land management agency stated that despite their personal assessment that climate change will impact ecosystem services and affect the forage available for livestock, there are significant obstacles to incorporating information from climate impacts models into some management decisions. Any adjustments to lease agreements must be legally defensible, and climate impacts model projections do not provide an adequate level of certainty. Along similar lines, some agency representatives felt they were unable to address climate change directly because of institutional priorities that focus on meeting specific standards and do not provide a mechanism pursuing additional goals or enforcing a more rigorous standard. At the air quality workshop a federal agency representative stated, "*Federal law establishes air quality standards, and we can't enforce polices (for example, policies pertaining to greenhouse gas emissions) beyond those standards*".

Acknowledging the challenges of managing specifically for climate change, many stakeholders were conscious of the many ways that the shifting climate may affect existing environmental concerns in the region. At the water quality workshop, a federal agency scientist referenced projections of declining snowpack and reduced summer snowmelt runoff, saying, "*Snowmelt is the cleanest water we get. If snowpack decreases, so does our supply of clean summer water and we'll need to make up with less clean groundwater*".

At the rangeland management workshop, two participants representing a family-owned cattle ranching business talked about challenges they faced in the context of climate change, with expected increases in the frequency and severity of drought. One of them said, "*[This past year] there were lots of sleepless nights thinking about the drought and what we would do to feed the cattle. We may have dodged the bullet this year but can't be sure about next year*".

These concerns were compounded by the fact that in drought conditions the price of hay rises, severely impacting ranch economics. In the forest management workshop, concerns were expressed about the potential for drier, hotter summers, and the linkages between reduced soil moisture and wildfire frequency and severity. An extension forester said, "*In systems where stand replacing fires were part of the ecology, fires increasingly behave very differently than they used to, sometimes causing permanent damage to soils*".

4.1.2. Land use change and development are key issues facing the region

Current and projected population growth and demographic shifts in Washington, Oregon and Idaho frequently rose to the forefront of discussions, with the dominant perception that these changes will lead to new pressures on the region's natural resources. This was particularly true of workshops focused on forest and rangelands management where participants shared personal experience of seeing privately owned land converted from working lands to rural residential uses. An extension forester said, "*In the next 15 years, we'll see the transfer of large amounts of forestland to several owners, a new generation. This may facilitate parcelization of forests and conversion of land for residential, suburban development*".

Those concerned with agricultural systems were also quick to identify shifts in land use as an important factor in the region. One soil and water conservation district scientist said, "*The issue* *of conversion of lands from agricultural to urban systems is huge. We also see major shifts from growing grass, and annual crop[s] to raspberries, which are perennial*". Shifting land uses will impact agricultural water demands and fertilizer and pesticide application regimes. Discussion also focused on changing demographics of farmers, for example in the dairy industry where market and regulatory pressures are likely to continue to favor large industrial operations that can streamline operations and small "craft" operations, but making the business climate inhospitable to mid-size family run dairy operations. Workshop participants made it clear that modeling scenarios that explicitly consider land use changes and evolving management practices would be necessary to have an accurate picture of how farming, ranching and forestry operations will impact, and be impacted by, environmental and natural resource concerns.

4.1.3. Scenarios of the region's future should explicitly analyze possible impacts of political and economic changes

Workshop questions designed to probe how integrated regional climate change impacts models might inform adaptation and mitigation activities led to discussions about the complexity of influencing social and individual behavior and choices. Participating stakeholders frequently expressed strong interest in regional models that explore plausible future political and economic scenarios (for example, scenarios related to markets, trade, regulations, and incentive programs). Revealing the need for integrated scenario planning, a federal agency water resources engineer said, "*There is a [mistaken] assumption in climate change adaptation planning that we have to plan for the future based on the past, we have to give choices based on old solutions. It's hard [yet necessary] to get people to think in a new way about approaches to problems*".

Specifically, interest in linking economic and biophysical models is widespread, with participants encouraging modelers to consider patterns of adoption of new technologies and changing policies and regulations when developing model scenarios. For example, an air quality manager from a state agency said, "*It would be really valuable to see the impact of large-scale shifts to public transportation on overall transportation emissions*". A research analyst at an NGO said, "*We should look at the potential for programs that pay landowners for ecosystem services and look at how layering different incentives could alter management*".

A natural resources extension specialist at the carbon and nitrogen management workshop asked, "*How do you integrate – other than economics – human ecology into this research?*" They went on to say, "*We can easily do economic optimization, but resource managers do not always do the thing economists predict they will do*", suggesting the need for scenarios informed by data from sociological and psychological studies as well as economic analyses. Some model features and dimensions of scenarios suggested by stakeholders were more feasible than others in the context of the BioEarth project. For example, it may be possible to incorporate the projected impacts of a riparin buffer protection regulation into a model scenario, but it would be more difficult to model changes in farm management practices that result from a public education campaign. Workshops participants clearly expressed that incorporating sociological and political dimensions of change into models, where possible, would greatly increase the relevance and usability of model outputs. Natural resource decision-makers would value seeing assumptions about social behavior clearly stated in communications of model results.

4.1.4. Impacts of decisions across jurisdictions and management sectors must be considered

The theme of unintended consequences arising from management decisions that were anticipated to have beneficial social and environmental impacts emerged at every BioEarth workshop. For example, in several of the workshops, natural resource decision-makers noted that developing regulations aimed at curtailing land use practices can lead to increased prevalence of that practice in the short run, as landowners seek to act before regulations take effect. Table 3 lists examples of observed and potential unintended consequences of management decisions that workshop participants discussed. The ability to understand feedback loops connecting different social and biophysical systems and bringing that understanding to bear in management decisions is not yet well developed.

Interactions between systems are inherently difficult to manage for because of competing frames of reference and diverse institutional objectives among resource management institutions. Natural resource decision-makers who participated in BioEarth workshops are concerned about already-observed and expected unintended consequences and see critical information needs related to these interactions and feedbacks between systems.

Cross-jurisdictional planning is more thoroughly incorporated in some sectors of natural resource decision-making than others. For example, Northwest US air quality managers tend to be engaged in a high level of collaboration between agencies. This may be largely due to the nature of atmospheric processes, characterized by rapid change over large areas and issues that are not confined by political borders. In forest and rangelands management, there is considerable variation in how different jurisdictions manage similar natural resource challenges.

We find that Northwest US stakeholders who work on issues related to regional water are aware of, and highly interested in, connections between water supply and water quality, especially as climate change alters timing and flow of water. Awareness of these intersections is emergent and not fully reflected in agency operations and planning. Understanding of linkages between different natural resource management concerns could potentially be supported through integrated regional environmental modeling efforts such as BioEarth.

4.2. Most relevant time horizons for climate change impacts projections

Depending on the natural resource systems that decision-makers focus on and the context in which they work, information about climate change impacts is most relevant when provided at specific temporal and scales and over particular time horizons. At each BioEarth workshop, participants were asked to consider the time horizon and temporal scale at which information about projected environmental impacts of changing climatic conditions and management practices would be most useful to them. Fig. 1 shows how natural resource decision-makers rated the usefulness of information about resource management practices projected at different timescales. Participants were asked to consider resource management practices pertaining to the specific environmental issue their workshop was focused on (i.e. air quality decision-makers considered temporal scales of information about air quality management practices).[1]

Among air quality decision-makers, 55% of the votes for most useful timescale for projecting the impacts of management decisions were for a sub-annual timescale. Similarly, among water quality decision-makers 45% of the votes were for timescales of less than one year. This is likely at least in part because water quality and air quality are explicitly regulated according to federal and state laws, including the Clean Water Act and the Clean Air Act. For example, having projections of air quality at a fine temporal scale

[1] Note that participants in the carbon and nitrogen management workshop were asked twice about useful timescales, once about carbon management and once about nitrogen management.

Table 3
Observed and possible unintended consequences of decisions.

Workshop focus	Examples of unintended consequences of resource management decisions mentioned by participating stakeholders
Water quality	• Adding nutrients to localized areas (e.g. within a reservoir) to support fish populations worsens eutrophication issues elsewhere in the system
Water supply	• Programs to promote adoption of technologies to enhance irrigation efficiency can lead to increased consumptive use (e.g. if farmers adjust their crop mix to more water intensive crops or expand their irrigated acreage).
Air quality	• Restrictions on burning wood products for heat in the Northwest lead to greater reliance on natural gas, natural gas extraction has environmental consequences in other regions • Shifting from growing dryland wheat to oilseeds can diversify cropping, but also leaves less residue on fields, resulting in more emissions of ultrafine particulate matter
Rangeland management	• Riparian restoration programs that demand complete cessation of ranch operations, aiming to protect vegetation near waterways, could lead to negative impacts on vegetation diversity
Forest management	• Using underbrush from regional forests for biofuels production may remove nutrients from the watershed • Controlled burns reduce risk of massive fires, but may also contribute to air quality issues
Nitrogen and carbon management	• Anaerobic digesters built to address methane emissions from dairies may produce higher NOx emissions • Some dairies compost manure to fulfill nitrogen management plan guidelines, but composting manure in some cases contributes to water quality issues, ammonia emissions and GHG emissions

could thus directly inform decisions about when to restrict burning. In general, air quality and water quality managers who make regulatory decisions at government agencies require model projections at sub-annual to annual time scales.

Decision-makers surveyed about timescales for projecting the impacts of nitrogen and carbon management activities judged projections made on a timescale of 1–2 years to be most useful. In the case of nitrogen management decisions the second most useful timescale selected was days-12 months, while for carbon management issues the second most useful timescale selected was 10–50 years. This difference may reflect the fact that patterns in the transportation and deposition of nitrogen shift seasonally, while on the other hand, for decision-makers interested in carbon sequestration potential of agricultural soils, relevant timescales are on the order of decades to centuries.

Preferences about most useful timescales for presenting model outputs were fairly evenly distributed among rangelands management stakeholders, reflecting the wide variety of decisions that rangeland managers make—from moving animals in pastures seasonally to designing policies about riparian buffer zones over decades. Many stakeholders representing agricultural and rangelands industries said that information at long timescales (10 years or greater) was less useful than information at shorter timescales. Natural resource decision-makers in industry typically make planning decisions according to investment horizons, and will find model results most meaningful when they correspond to those time scales.

Management decisions associated with forests, both from a forest ecosystems conservation perspective and a forest products industry perspective, are generally made considering longer intervals of time because of the rate at which forests grow and the intervals at which decisions about harvesting and management are made. Thirty-five percent of forest management stakeholders said that the most useful time scale for projecting impacts of management decisions was 10–50 years. Twenty-five percent selected "other" when answering this question and remarked that they were interested in the fate of forests in the next century and beyond.

4.3. Most relevant spatial scales for climate change impacts projections

When natural resource decision-makers discussed spatial scales at which model outputs would be most relevant to their work, interest in fine-scale and broad-scale outputs was more common than interest in seeing "mid-scale" results presented. For example, in the water quality management workshop, participants were evenly divided as to whether projections at the land parcel/farm scale, river reach scale or watershed-scale would be most useful, while there was low interest in seeing medium-scale outputs, for example at the county level. Discussing the importance of fine-scale results, one representative of an environmental consulting group attending the air quality workshop noted that land use models are never high-resolution enough to conclusively determine whether the majority of pollutants in a watershed originate from wood stoves or diesel trucks. Similarly, at the water quality workshop an NGO representative stated that fine-scale projections were needed to identify cold-water zones in streams, which are critical for salmon habitat.

At the same time that fine-scale model outputs are valuable for many specific land use and resource management planning applications, science educators, communicators and policy makers may benefit most from having broad-scale model outputs that present regional projections with uncertainty quantified and clearly communicated for a non-specialist audience.

4.4. Expectations of climate modeling research

In pre-workshop surveys, participants were asked what they expected from BioEarth workshops. In post-workshop surveys online participants were asked to evaluate how those expectations evolved after hearing presentations from scientists, discussing the challenges that they saw on the horizon, and considering scenarios and model outputs that may inform their decisions. In the pre-workshop surveys the majority of participants made comments along the lines of a water resources engineer who said, "*No expectations really, I am here to learn and provide input*". Several participants expected the workshop to be a learning opportunity, for example, "*I expect to learn more about the modeling approach as it relates to agricultural air quality issues*". Others regarded the workshop as a chance to bring the research community together with NGO and industry stakeholders who can effect change.

In post-workshop evaluations, typical stakeholder comments conveyed interest in BioEarth while expressing uncertainty about the ultimate relevance of the modeling effort to their work. For example, "*The usefulness of models of this expanse and complexity is uncertain, so I'm in a 'wait and see' mode*". Roughly 25% of the respondents were unreservedly optimistic. Said one stakeholder, "*They will generate some really interesting results about present and future water quantity, quality and land use in the region. I will be paying attention to this work in the future and look forward to more news and results*". Another 25% of participants left the workshop with skepticism that the research project would yield meaningful outcomes for their work, for example, "*I hope that there are tangible applications to a variety of users, but I fear this may not be the case*". When resource mangers have diverse and highly specific

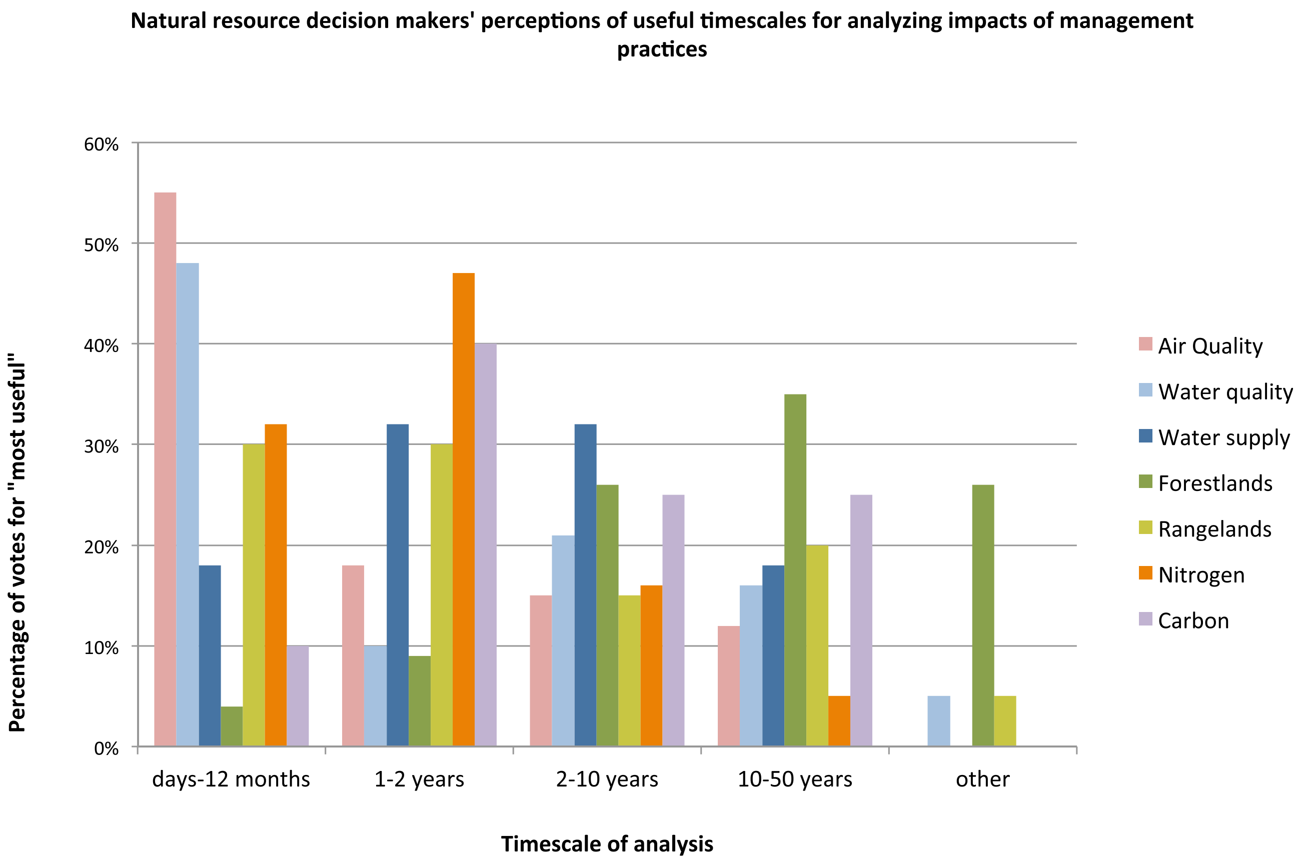

Fig. 1. Percentage of votes for "most useful" for each timescale at which the impacts of management practices might be modeled.

information needs, it is challenging to pursue modeling approaches and generate model outputs that are universally relevant.

Stakeholders' expectations should be viewed in light of typical sources of information upon which they base decisions. In the pre-workshop survey participants were asked, "What kinds of academic research and scientific data are most valuable and/or relevant to your decision-making?" Respondents selected all the options that applied to them: 57% percent of the votes were for earth and life sciences (hydrology, biology, crop and soil science, botany), followed by 17% for economics, 14% for policy, history and social sciences, and 8% for sociology and psychology. Another 3% of the votes were for "other". Written-in responses to the questions about the most valuable and relevant fields of study were toxicology, public health, epidemiology, and chemistry. The general tendency to rank information from earth and life sciences as most meaningful for natural resource management decision-making is interesting to note given stakeholders' strong interest in seeing models that integrate projections based on economic, behavioral and sociological analyses of the region. This result points to continued need to integrate social, economic and biophysical knowledge and research approaches.

Before the workshop, stakeholders were asked to consider the question, "How well do researchers in academia communicate their findings to stakeholders?" After the workshop, they were asked, "Based on your experience at this meeting, how well do you think researchers communicated their work to stakeholders?" Participants' responses to these questions posed before and after the workshops are presented in Fig. 2.

The difference in responses to these two questions indicates that workshop participants on the whole had a markedly better opinion of climate researchers' communication after the workshop. Clearly the communication and engagement in the workshop had some influence. Although determining an optimal design for the workshop engagement process is challenging, these results suggest that having a communication strategy that deliberately seeks to address barriers between researchers and stakeholders, and includes individuals with boundary spanning skills, has a positive effect on stakeholder perceptions of academic science communication.

Participants shared many questions they were grappling with that they hoped the BioEarth modeling framework might help address. An NGO representative at the carbon and nitrogen management workshop asked, "*Can we point to ways to reduce the N_2O emissions, and also understand the changes we'll see in soil behavior with nitrogen and carbon as it gets warmer?*" At the water supply workshop, a water resources consultant said, "*If the model could give explicit, quantitative scenarios about soil carbon management in forestry, and how that affects water supply and water availability this would help policy makers make decisions*". While there were strong expressions of interest in seeing outputs of an environmental model that considers feedbacks and linkages between systems and considers socioeconomic change factors, workshop participants were cognizant of the challenges associated with using models for decision-making. A participating extension forester said, "*People have concerns about the transparency of models. They have an ingrained distrust of models. I would hope that one project output would be to bring people along in terms of developing a broad literacy of modeling, and how you, as a consumer, evaluate it… What a model is, and what it isn't.*" Even considering limitations to environmental model use in decision-making, there is strong interest in participating in climate change impacts research efforts based at universities to promote development of useable model outputs.

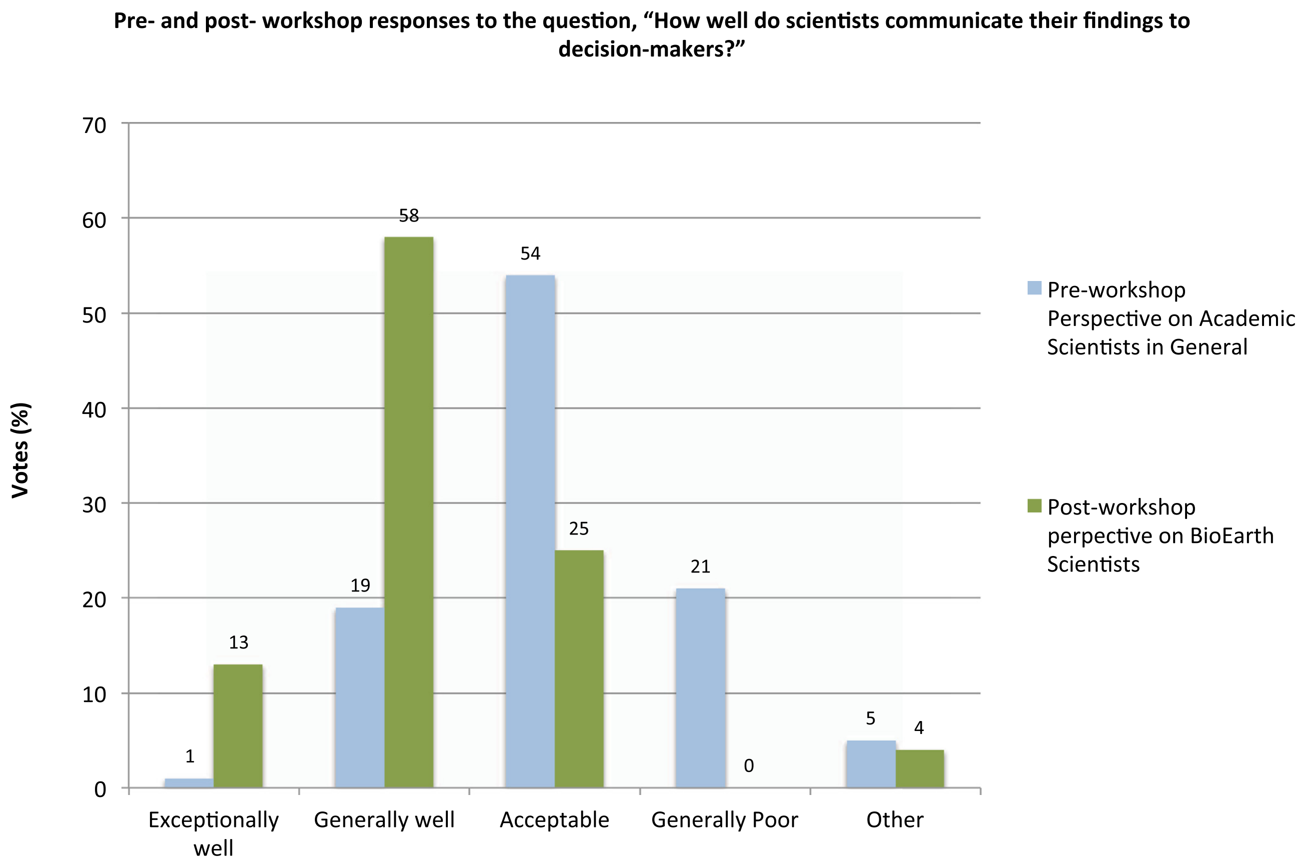

Fig. 2. Workshop participants' pre- and post-workshop responses to questions about how well scientists communicate with decision-makers.

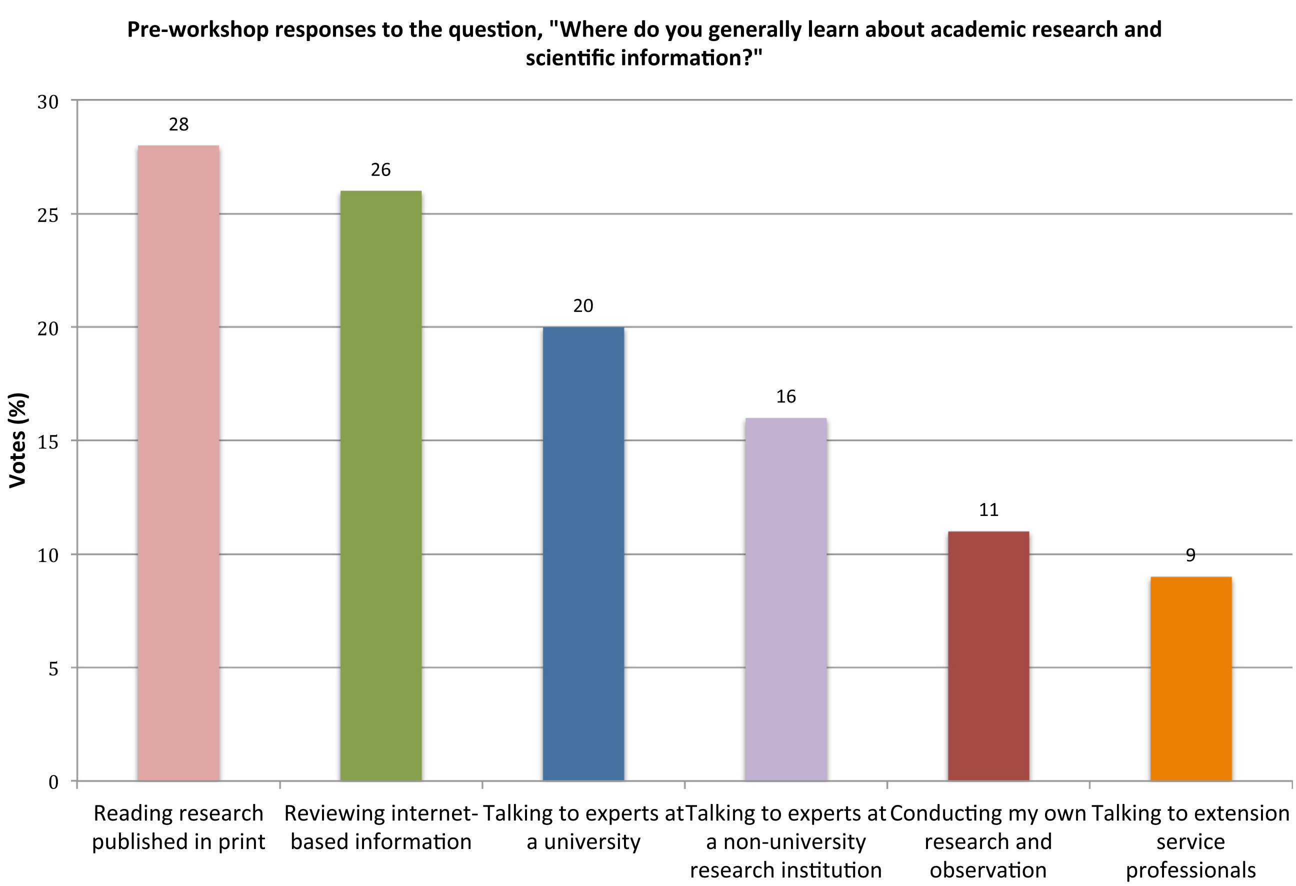

Fig. 3. Self-reported sources of scientific information among natural resource management decision-makers.

4.5. Structuring scientist-stakeholder communication and engagement to develop usable models

Learning about how regional natural resource decision-makers would like to see climate change impacts projections and other environmental modeling results presented and communicated was one of the central goals of the BioEarth stakeholder workshops. Before workshops participants were asked, "where do you generally learn about academic research and scientific information?" Respondents selected all options that applied to them; in total there were 149 responses (Fig. 3). The most common sources of scientific information used by participants are reports in print and online. Direct conversations with scientists, whether they are based at universities or other research institutions, are also key pathways for stakeholders to learn about regional climate change impacts.

Stakeholders frequently made comments reflecting the value they placed on sustained collaborative processes between academic researchers and natural resource management stakeholders. A soil and water conservation district scientist said, "*To actually impact decision-making you have to have intimate knowledge of specific stakeholders' decisions, for example, growers. You need to sit with them and understand how they make decisions to understand it well enough to see how science could be brought to bear on their decisions*". This quote attests to the value of making efficient stakeholder engagement central to climate research efforts and utilizing the boundary spanning skills of individuals trained as facilitators and science communicators. A forester said, "*These questions are complex. Any models we have are likely to be inaccurate. Some credible way of demonstrating model accuracy is critical for developing stakeholder confidence*". Comments such as this underscore the need for education opportunities for academic researchers to hone communication skills and education opportunities for decision-makers to become better versed in environment modeling. Recommendations for model development made by participating stakeholders in post workshop surveys were coded and analyzed. Table 4 summarizes the most frequent recommendations from natural resource decision-makers with different professional roles about developing usable climate models.

Table 4
Recommendations about approaches to developing decision-relevant climate change impacts models.

Professional role	Frequent recommendations
Public resource manager	• Clearly presenting model assumptions and sources of uncertainty helps decision-makers interpret the relevance to model outputs to policy decisions • Agency mandates often limit the degree to which cross-sector system interactions can be considered; university-led research can be a resource for exploring cross-sector and cross-jurisdictional issues
Private resource manager	• Industry stakeholders managing agricultural, rangeland and forest resources are most interested in time horizons relevant to the commodities they produce. They often desire fine spatial scale projections • There is strong interest in comparing outcomes of specific land management practices and comparing "best and worst" management practices
Researcher	• Researchers encourage utilizing regional socioeconomic pathway scenarios that are consistent across research efforts conducted at different institutions • Platforms for enhancing sharing of models and raw data are desired
Educator/communicator	• Science educators and communicators urge researchers to share climate impacts model outputs as accessible graphs and maps, including interpretation of results • Researchers were encouraged to interface with extension service professionals and others who work directly with landowners to increase visibility and accessibility of their science
Policy advocate	• Specific policy changes expected in the future should be modeled to evaluate their potential positive benefits and limitations • Sharing "straw man" model outputs is an important way for stakeholders to learn about how models are developed and to provide feedback to researchers

5. Conclusions

Regional climate change impacts modeling is of great interest and considerable potential utility to natural resource management decision-makers, but gaps in the relevance and accessibility of model outputs persist. Stakeholders' eagerness to engage with the BioEarth modeling team suggests that awareness of the value of an integrated approach to resource management is growing. Natural resource decision-makers increasingly recognize feedbacks among atmospheric, hydrologic, agricultural and forest systems and are interested in holistic management approaches that do not consider these environmental systems to be partitioned. Enhancing the relevance and usability of climate services information for natural resource decision-makers will continue to be a challenge because of the range and complexity of climate change impacts on natural and managed systems. Insights from this project provide valuable guidance for similar research initiatives seeking to support scientist-stakeholder dialogue and collaborative, decision-relevant regional environmental models.

Northwest US natural resource decision-makers who participated in BioEarth workshops demonstrated a strong interest in seeing accessible climate change impacts projections that go beyond biophysical modeling to consider how economic, social and political changes may interact with climatic drivers of change. Participants' specific information needs, future scenarios of interest and desired formats for model results varied according to the different environmental systems they focus on and their professional roles.

Coordinating efficient engagement activities depends on establishing partnerships with government agencies, non-profit organizations, industry groups and individuals over time. Embedding individuals with facilitation and communication experience in research teams is vitally important to conduct preliminary analysis of potential stakeholder groups, coordinate forums for information sharing and to maintain collaboration and information sharing among stakeholders and modelers over time. The communication working group observed that when researchers clearly present how models operate and show concrete examples of model applications, stakeholders were able to provide actionable input to researchers. Workshops arranged around environmental systems (water, air, forests, etc.) enabled generative dialogue among individuals from different institutional contexts who share overlapping expertise and concerns. At the same time, there may be benefits to encouraging dialogue across management sectors, for instance bringing water supply and water quality professionals together to consider management concerns in the context of climate change.

Natural resource decision-makers' information needs are complex and variable across different systems and different professional roles. As such, climate change impacts research teams must invest considerable time, funding and expertise in ensuring a match between model capabilities and decision-makers' information needs. This finding points to the necessity of planning for stakeholder engagement processes in the early phases of project design and proposal writing. In order to prepare for and conduct stakeholder workshops that inform model development, planning for those workshops must begin far in advance of model development. Thus, effective stakeholder engagement processes demand that funding and support for this component of the research process be established from the outset of project design.

Hearing stakeholders' specific priority information needs is critical for researchers seeking to develop decision-relevant environmental models. For university-based researchers involved in the BioEarth research initiative, input from stakeholders during workshops influenced the shift of focus away from creating a single integrated model, towards developing the capability to link specific components of the earth system that are relevant to a decision-making question. For example, stakeholder questions related to sustaining irrigated agricultural production in a changing climate did not necessitate full integration with an atmospheric model, whereas questions about drought and agricultural dust require a separate and unique linkage of models. We anticipate that BioEarth workshop results will continue to inform regional research activities beyond the duration of the project itself, not only in shaping model development priorities, but also guiding instances of model application and informing how findings are communicated and disseminated.

Regional climate change impacts models present a critical opportunity to consider how observed and projected land use changes will interact with climate change impacts. Northwest US natural resource decision-makers participating in BioEarth workshops recognized that many vulnerabilities associated with climate change impacts are highly variable over space and time, thus regionally and locally specific projections are needed to manage risks and identify opportunities for mitigation and adaptation actions. Through modeling, researchers and decision-makers can explore the outcomes of current best management practices vs. what are understood to be "worst practices".

When natural resource decision-makers have a chance to learn about how models and scenarios are developed, it becomes possible for those stakeholders to evaluate the relevance of the model for a particular decision. Input from natural resource managers engaged in this research underscores the importance of researchers sharing preliminary model outputs with stakeholders in order to foster discussion about approaches to linking models, assumptions embedded in modeled scenarios and sources of uncertainty.

On the basis of input from natural resource decision-makers at BioEarth workshops we recommend that regional environmental modeling teams striving for enhanced societal relevance and application of models in natural resource decision-making processes conduct thorough background research about potential stakeholder partners in government agencies, industry, and non governmental organizations and engage those diverse stakeholders early in the modeling process. Using a combination of pre and post workshop surveys and focus group discussions during workshops was an effective practice to identify stakeholder priorities related to environmental change concerns and information needs. Workshops served as a forum for cross-sector dialogue about climate change impacts of concern, expected policy changes, emerging technologies and possible unintended consequences of management practices. Discussion of future scenarios of interest and relevant temporal and spatial scales for model outputs is critical for the production of actionable climate change impacts projections. Ultimately, creating a forum for discussion among researchers and stakeholders representing diverse professional roles and backgrounds enhanced researchers' understanding of the social and political systems in which stakeholders work and the considerations that they weigh when making decisions about resource management and policies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cliser.2017.03.002.

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