Julie Koppel Maldonado
Benedict Colombi
Rajul Pandya *Editors*

Climate Change and Indigenous Peoples in the United States

Impacts, Experiences and Actions

Springer

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Previously published in *Climatic Change*
Volume 120, issue 3, 2013

Springer

Editors
Julie Koppel Maldonado
Department of Anthropology
American University
Washington, DC, USA

Benedict Colombi
American Indian Studies
University of Arizona
Tucson, AZ, USA

Rajul Pandya
University Corporation
for Atmospheric Research
Boulder, CO, USA

ISBN 978-3-319-05265-6 ISBN 978-3-319-05266-3 (eBook)
DOI 10.1007/978-3-319-05266-3
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014933282

Front cover picture: Laura Gephart
Rear cover logo: Columbia River Inter-Tribal Fish Commission (CRITFC)

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Climate change and other human-induced changes are impacting the tribal natural and cultural resources of indigenous people throughout the United States. As these impacts become more severe, traditional ecological knowledge (TEK) systems provide significant understanding of ecological changes and help identify adaptive strategies for both indigenous and non-indigenous communities around the world.

Recognizing the importance of this insight, authors of the Draft Third National Climate Assessment Tribal chapter called for a respectful summary of indigenous observations, understandings, experiences and adaptive strategies to climate change. As a result, nearly fifty authors representing tribal communities, academia, government agencies and NGOs came together to create a Special Issue edition for the journal *Climatic Change*, “Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions” (Vol. 20, Issue 3). The Special Issue represented the first time a peer-reviewed scientific journal exclusively devoted an entire edition to climate change and its impacts on indigenous communities across the United States.

The chapters in this book address some of the most pertinent issues being experienced by indigenous communities in the U.S. due to climate change and other human-induced stressors, including loss of traditional knowledge; Arctic sea ice loss and permafrost thaw; forced displacement and relocation; and threats to forests and ecosystems, food security and traditional foods, water quality and quantity, and the multi-generational subsistence-based livelihoods and cultural value systems which shape indigenous practices and identities. The case studies offer an inclusive view of how indigenous peoples throughout the U.S. are observing, experiencing, mitigating and adapting to climate change, which provides relevant insight for indigenous peoples and communities facing similar circumstances worldwide.

The book also highlights how tribal communities and programs are responding to the changing environments and the active collaborations taking place between tribes and academic institutions, as well as between tribes and governmental agencies and non-governmental organizations. The collaborative effort between indigenous and non-indigenous representatives to create the Special Issue and this book and the case studies highlighted in the chapters show the importance of people coming together in strategic and respectful partnerships.

The chapters include recommendations that such partnerships should be based on a just system of responsibilities guided by the principles of justice and human rights and how in establishing greater self-governance mechanisms and partnerships, it is particularly important to pay attention to what is happening at the local level. The case studies included highlight the key role of TEK and indigenous science in climate change research and in developing adaptation strategies. We hope this body of work plays a small role in demonstrating how knowledge and action are intimately linked in the efforts indigenous people are leading to adapt to and mitigate against the impacts of climate change.

As Prof. Dan Wildcat, Haskell Indian Nations University and book contributor, said about the information in this book, “The partnerships between tribal peoples and their non-tribal research allies give us a model for responsible and respectful international collaboration that will be essential to successfully mitigate the most damaging effects of climate change that have yet to arrive. Climate change and this Special Issue remind us that, as my Lakota relatives say, ‘We are all related.’ That might be the wisdom we need most, whether scientist or non-scientist - Indigenous or non-Indigenous.”

Special thanks to all of the contributing authors who made this publication possible and for their years of work, research and action that have inspired the work contained within; to the authors of the Indigenous Peoples Chapter for the 3rd National Climate Assessment – T.M. Bull Bennett, Nancy Maynard, Patricia Cochran, Robert Gough, Kathy Lynn, Garrit Voggesser and Susan Wotkyns – for all of their countless hours dedicated to putting the issues addressed in this book front and center on the national stage; to Kathy Jacobs, Director of the 3rd National Climate Assessment, for her support and inspiration to initiate this effort; to the reviewers for helping us shape this body of work; and to the editors of *Climatic Change* journal for their support throughout this process.

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DOI 10.1007/978-3-319-05266-3_1
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0849-6

Introduction: climate change and indigenous peoples of the USA

Daniel R. Wildcat

Received: 11 December 2012 / Accepted: 16 July 2013 / Published online: 15 August 2013

This special issue of *Climatic Change*, dedicated to the examination of impacts of climate change on indigenous peoples and their homelands, and proposed strategies of adaptation, constitutes a compelling and timely report on what is happening in Native homelands and communities. Indigenous peoples and marginalized populations are particularly exposed and sensitive to climate change impacts due to their resource-based livelihoods and the location of their homes in vulnerable environments. While these articles focus on indigenous peoples found within the borders of the USA, J. Maldonado et al. point out in their contribution, "The Impact of Climate Change on Tribal Communities in the U.S.: Displacement, Relocation, and Human Rights," that indigenous communities around the world face similar issues and will likely find the contributions here valuable.

These articles confirm what those of us who have been paying attention to our homelands already know: the world we live in is changing, not the interior spaces and places where the majority of us situated in the midst of the modern industrial and postindustrial societies spend our days and nights, but the world of unbounded landscapes and seascapes that constitute what humankind denominates the natural world. Climate change, however, is only one of many drivers of change. Its effects cannot be isolated from the multiple social, political, economic, and environmental changes confronting present-day indigenous and marginalized communities. Indigenous peoples have long and multi-generational histories of interaction with their environments that include coping with environmental uncertainty, variability, and change. Collectively, these articles give us a glimpse of the day-to-day climate change reality those native people experience who still find their tribal identities and lifeways in practical activities situated in the symbiotic relationships of the nature–culture nexus.

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

D. R. Wildcat
Muscogee (Creek) Nation, Okmulgee, USA

D. R. Wildcat (✉)
Indigenous Peoples Climate Change Working Group, Haskell Indian Nations University,
Lawrence, KS, USA
e-mail: dwildcat@sunflower.com

These articles highlight why awareness of climate change is so high among indigenous peoples of the USA when compared to most citizens of the USA. Unlike most citizens who form opinions about climate change based on cable news networks, internet sites, and even paper news publications, American Indian and Alaska Native awareness of climate change is the result of practical lifeway experiences and sensitivity to the rhythms of seasons that make them particularly knowledgeable about what is going on where they live. The recent UNESCO and UN publication of *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation* (2012) by D.J. Nakashima et al. documents that indigenous peoples have been able to draw on a long multi-generational transmission of traditional ecological knowledges (TEKs) to demonstrate keen response and adaptation capabilities in the face of climate change.

Unlike the increasingly geographically mobile population of the USA, indigenous peoples draw on practical lifeway experiences—not one person's experience—but that of entire nations and communities to share multi-generational "deep spatial" knowledges of empirical landscapes and seascapes. In scientific terms, these traditional knowledges (TKs) and/or TEKs are much akin to longitudinal case or field studies, with two exceptions: modern scientific studies are lucky to be designed and funded for a decade or two and they almost never have the rich experiential character of TKs. Also, to reiterate, indigenous peoples' awareness of climate change effects and possible adaptation strategies to address those effects are born of practical lifeway exigencies and experiences accumulated over extremely long periods of time in particular places where home is identified with ecosystems and natural environments, not street addresses.

The useful knowledge of climate change and its challenges to Native people and native homelands offered here is far from exhaustive. The population of American Indians/Alaska Natives in the USA is approximately 5.2 million and Hawaiian Natives/Pacific Islanders number approximately 1.2 million. Few people realize that there are 566 federally recognized tribes and, at least, 34 state-recognized tribes across the USA situated in every type of environment found in the USA This issue of *Climatic Change* deals with a good sample of those tribes and those willing to read every article presented here will glimpse the "big picture" of Native America too few Americans recognize: the history of this blue green planet—what many indigenous peoples throughout the Americas call Mother Earth—is essentially a story of intertwined ecological and cultural diversity.

This "big" history of people and places on the planet is now more important for the public to understand than any single national, biographical, or episodic-based history for a number of reasons, but one stands out. American Indian and Alaska Native cultural and lifeway diversity expressed through the symbiotic nature–culture nexus reminds all of us that our human responses to climate change will require diverse strategies that fit the people and places of the planet—in all of their diversity. There is no silver bullet or one-size-fits-all solution for addressing the impacts of climate change.

The contribution, "Indigenous Frameworks for Observing and Responding to Climate Change in Alaska," by P. Cochran et al. is invaluable for emphasizing the importance of the inclusion indigenous peoples, their complex worldviews, and TKs in understanding climate change and adaptation strategies required to deal with climate change impacts. Cochran et al. document the complementary features of indigenous worldviews and the traditional knowledges they produce relative to Earth system science and persuasively argue for their necessary inclusion in climate change research, especially for the ethical framework they provide. Cochran et al. state, "From this knowledge emerges an indigenous sense of place, language, ceremonies, cultural identities, and ways of life that provide an ethical framework that guides responses to change." An overarching theme that emerges throughout this collection of articles is the necessity for respectful partnering and collaboration of indigenous peoples and their communities with non-indigenous governments and organizations if climate change impacts are to be successfully, i.e., sustainably, addressed. Cochran et al. make invaluable suggestions based on years of experience about what needs to be done to create the social and cultural "climate change," required to establish what both K.P. Whyte and Hardison and Williams argue in their contribution to this issue *Climatic Change*, should be relationships based on justice.

K.P. Whyte's article, "Justice Forward: Tribes, Climate Adaptation and Responsibility," accurately suggests that one of the difficult challenges we must face in the USA is how to respond to climate change in ways that are just. Whyte's analysis of institutional frameworks and mechanisms for realizing justice in our adaptations to climate change is timely and in itself challenging. In many respects, the physical features of climate change are much easier to understand and estimate than are the ways in which we can exercise human responses to those changes that embrace and realize justice. While the political, legal, and governmental situations of indigenous peoples vary widely across the planet, Whyte's institutional analysis of justice can serve as a useful tool for other's across the planet to ponder in addressing the difficult social dimensions of climate change.

Many of us see the indispensible value of incorporating traditional knowledges into adaptation strategies, but Hardison and Williams's contribution, " Culture, Law, Risk and Governance: the Ecology of Traditional Knowledge in Climate Change Adaptation," points out the potential downside indigenous peoples face when asked to share traditional knowledges. The potential for exploitation and misuse of traditional knowledges is real—as is the incompatibility between legal rational constructions of copyrights, contracts, and licensure tools to deal justly with indigenous knowledge(s). As the authors point out, "Once traditional knowledge is shared outside of a community, it enters alien social and legal contexts." Consequently, it is not surprising, given the potential abuse and misuse of traditional knowledge, the cooperative partnerships many see as crucial to successful adaptation to climate change is seldom happening.

Hardison and Williams challenge all of us working at the intersection of Western law and science, and traditional knowledge to consider the development of a governance mechanism to guide the sharing of traditional knowledges. By arguing that indigenous traditional knowledge should be understood as "a sovereign property with its own rules and laws determined by its proper sovereign", they affirm Article 31 of the United Nations Declaration on the Rights of Indigenous Peoples. They also suggest the guiding principle for sharing indigenous traditional knowledge "should be based on free, prior and informed consent and mutually agreed terms based on equal standing." Moving beyond dialogues about how TK data can be integrated into existing resource management plans the authors remind us of the importance of carefully examining how TK experts are integrated in a just and meaningful resource management process.

J. Maldonado et al. point out in their article on climate change adaptation, displacement, relocation, and migration as fundamental human rights issues that considerable "heavy lifting" awaits our national and international governmental institutions. Their discussions of the situations facing the Alaska villages of Kivalina and Newtok, and the Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Indians of Louisiana (a state—not federally—recognized tribe), highlight the governmental and institutional "no-man's land" these indigenous communities experience in seeking ways to retain their unique cultural lifeways and governmental traditions in a sustainable manner. The problems these three indigenous communities face are complex and demanding: especially demanding of justice. The articles by Whyte, Hardison and Williams, and Maldonado et al. remind us that the effects of climate change are complicated and hardly an abstraction for many indigenous nations and communities in the USA.

At a basic level, climate change is all about water: some people and places will have a lot less of it than they had before the anthropogenic warming of the planet and others will have a lot more of it—often in places where they would prefer not to have it. Not surprisingly, 4 of the 12 articles here focus on water. Cozzetto et al. in, "Climate Change Impacts on the Water Resources of American Indians and Alaska Natives in the U.S.," survey the impacts of climate change very broadly on water resources in six regions of the continental USA and make recommendations for water resource climate preparedness. In all cases, the impacts are complex given the range of other factors that can affect water quality and quantity, and the impacts vary from region to region. Like Cochran et al. and many contributors to this issue of *Climatic Change*, Cozzetto et al. call for the use of TEK in assessing impacts and developing mitigation/adaptation plans to deal with climate change. They too sound the most consistent theme running throughout this collection of articles—indigenous peoples will need to establish partnerships with non-tribal entities in order to sustainably address water resource climate preparedness.

M. Gautam, Chief, and Smith emphasize the same point in their article, "Climate Change in Arid Lands and Native American Vulnerability: The Case of the Pyramid Lake Paiute Tribe," and make another crucial point: tribal vulnerabilities in the case of the Pyramid Lake Paiute (PLP) Tribe include threats to deep-rooted cultural beliefs, values, and practices that constitute the core of what it means to be Pyramid Lake Paiute. In the case of the PLP, the authors point out that the key tribal climate change vulnerability they face is to Pyramid Lake and the Cui-ui fish. Their analysis of PLP household survey's and semi-structured interviews with tribal executives on values, beliefs, and perception regarding climate change demonstrates that the PLP know what is happening within the landscapes/seascapes of their homelands, including the intergovernmental environment and differing cultural values and worldviews they must navigate to maintain their unique identities as indigenous Peoples.

The articles focusing on climate impacts on rivers and salmon of the Northwest, "Changing Streamflow on Columbia Basin Tribal Lands—Climate Change and Salmon," by Kyle Dittmer, and "The Effect of Climate Change on Glacier Ablation and Baseflow Support in the Nooksack River Basin and Implications on Pacific Salmon Species Protection and Recovery," by O. Grah and J. Beaulieu illustrate the complexity of impacts and the need for cooperative concerted intergovernmental efforts to address climate change-induced threats. K. Dittmer et al. and Grah and Beaulieu find that the impacts of climate change on of the Columbia River Basin and the Nooksack Basin, respectively, will pose serious threats to the salmon and the cultural, religious and ceremonial, commercial, and subsistence activities of the Native peoples of these river basins. Citing the publication, "Salmon Culture", by the Columbia River Inter-Tribal Fish Commission, consisting of representatives from the Nez Perce Tribe, the Confederated Tribes of the Umatilla Indian Reservation, the Yakama Nation, and the Confederated Tribes of Warm Springs Reservation of Oregon, Dittmer states, "Salmon are more than just a major food source—it is an important part of tribal religion and culture."

Using data collected from snow telemetry (SNOTEL) stations in the Nooksack watershed and published studies, Grah and Beaulieu find that the stream flow of the Nooksack has decreased in the summer, temperatures have warmed, and the peak runoff period occurs earlier. These findings, supported by aerial data, suggest that as glacial extent decreases among the glaciers feeding the Nooksack, reduced baseflows and higher water temperatures are likely to create more stressful conditions for salmonids, potentially pushing temperatures to lethal levels for fish that are central to Nooksak Indian Tribal culture and lifeways.

Dittmer analyzes GIS-based PRISM temperature and precipitation data, and USGS stream flow data, using linear trend analysis for the Columbia River and its tributaries to assess climate change impacts on Columbia River Basin tribal reservations and historical tribal lands. Even factoring in the inter-annual climate variability effects of the El Nino-Southern Oscillation and Pacific Decadal Oscillation, they find warming air temperatures and the increase in 100-year November/December floods "could push enough runoff to scour the stream bed and disrupt or destroy redds (i.e., egg nest), which fall chinook, coho, and steelhead construct in September and October."

No two river basins are the same, but the research by Dittmer and Grah and Beaulieu confirm what the tribal peoples on these Pacific Northwest rivers are experiencing right now—climate change that is negatively affecting the water flow levels, timing of peak flows, and temperatures to impact salmonids and peoples who found their indigenous identities and cultures in their relationships with rivers and salmon. Both articles illustrate that habitat restoration is an environmental justice issue that speaks directly to what few modern peoples directly experience today—our human stories of life on this planet are inseparable from the larger and diverse life-system stories of the planet.

Understanding the climate change threats to US rivers and lakes, it should come as no surprise that forests and their associated ecosystems do not fare much better. In "Cultural Impacts to Tribes from Climate Change Influences on Forests," G. Voggesser et al. survey threats to forests, e.g., sudden oak death, emerald ash borer, invasive species, and wildfires, and find that changes in species composition in forests and other ecosystems will require "robust federal–tribal relationships" if negative impacts on "tribal subsistence, culture, and economy" are to be effectively addressed. They too affirm the importance of the inclusion of TEK when investigating adaptation strategies to deal with climate change impacts and note its holistic advantage—another theme running through many of the contributions to this issue of *Climatic Change*.

"Exploring Effects of Climate Change on Northern Plains American Indian Health," by J. Doyl et al., provides a case study focused on health-related water quality and quantity issues for the Crow Tribe and a nice summary of existing reports and literature on the health effects of climate change on Alaska Natives. The authors examine meteorological data collected from NOAA weather station in Hardin, Montana located on the reservation's northern border and US Geological Survey discharge data for the Little Bighorn River. They find dangerous levels of *Escherichia coli* are often found in the lower reaches of the Little Bighorn River. This finding and the recent appearance of lesions on catfish caught in the river are associated with warmer summers and possible increased sedimentation pollution resulting from the earlier spring runoff. These findings and two devastating floods in the last decade, Doyle, et al. point out, pose climate change-related health threats to those living on the Crow Reservation and in Big Horn County.

Doyle et al. emphasize that multiple dimensions of human health are affected by climate change. They point out that research is needed to understand and document the extent of the ecological and human health impacts of climate change. They conclude that a climate change health assessment is necessary for those living in Little Big Horn River basin to fully capture "the ecological effects of less snowfall, warmer temperatures, reduced stream flow and possibly increased flood frequency and fire severity currently experienced by Crow Tribal members and other residents of Big Horn County". Like Doyle et al., contributors to this issue of *Climatic Change* understand that such an assessment would benefit by listening to what community members have observed in a landscape and river they know well. Decision-making processes for climate action are most effective if they are accountable and responsive to the populations that are affected, and provide support for full and effective participation and representation in climate governance.

Nowhere is the discussion of change so palpable as in the article by K. Lynn et al. "The Impacts of Climate Change on Tribal Traditional Foods." They document the difficulty indigenous peoples in the USA have maintaining traditional healthy diets in the world we now live in. They show how climate change is exacerbating the problems associated with traditional food-ways, e.g., the colonial political and legal restrictions placed on First Nations Peoples that make it difficult to harvest traditional plant and animal food sources and the larger dominant society's socioeconomic-driven popular food culture. The authors point out, like other contributors in this issue of *Climatic Change*, that climate change will only make the maintenance traditional foods and the required subsistence activities to provide such diets very challenging. In light of the threats the American Indian and Alaska Natives face, it is not surprising that more and more Native meetings are convened under the title of security—food, water, energy, cultural, etc.

J. Reo and A. Parker's contribution, "Re-thinking Colonialism to Prepare for the Impacts of Rapid Environmental Change," suggests that there could be useful results for tribes and policy makers in a comparison of the early colonial impacts on the coupled human and natural systems of New England and the current Climate change impacts presently experienced and forecasted for the near future. Their article successfully argues that both events are marked by dramatic changes for both peoples and places of New England and consequently a critical historical examination of the dramatic anthropogenic changes to the homelands of the first peoples of New England could be very useful for future planning. Like so many other Native contributions to this special issue of *Climatic Change*, they not only give a picture of the climate impacts now experienced and forecasted, they remind everyone the first peoples of this land understood something scientists and policy makers need to understand, now more than ever, if humankind is to sustainably address the incredible negative climate change impacts facing not only tribes but all of humankind on this Mother Earth—sustainability requires the recognition and restoration of reciprocal relationships between peoples and places.

The value of the scientific and scholarly analyses, research, and reports offered in this issue of *Climatic Change*, "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions," taken as whole not only exists in the presentation of the difficult challenges climate change now poses for indigenous peoples of the USA, but in the clear message that climate change is not confined by human-made borders and boundaries. Successful, i.e., sustainable, climate change adaptation will require considerable "imagination," as N. Scott Momaday properly called it (see Reo and Parker), especially in the institution building (see Whyte) that will allow relationships of responsibility and respect to be created so American Indians and Alaska Natives can find some justice in climate mitigation and adaptation actions. This finds resonance with literature calling for "transformative" approaches to adaptation. The term "transformative" is being used to describe a range of endeavors that promise extraordinary outcomes.

That American Indian and Alaska Native scholars, community leaders, and scientists who have teamed with non-native scientists to produce this timely issue of *Climatic Change* is worth special note, too. For this collection of articles shows that respectful and responsible collaboration is possible between indigenous and non-indigenous people. Just as importantly, it illustrates that there is going to be plenty of work for everyone, indigenous and non-indigenous community members and leaders, physical and social scientists, policy makers, teachers, engineers, entrepreneurs, etc., if we are going to find diverse and sustainable responses to climate change.

Something else equally obvious, but possibly more provocative, strikes me after digesting these articles, the realization that indigenous Peoples or the First Nations of North America must not only assume the leadership roles in addressing climate change adaptation strategies on their present colonially determined reservations, but for their extensive ancestral and traditional territorial lands. Why? We must do so, not because it is our right, but because in so many of our worldviews and the institutions that sustain our indigenous lifeways, we understand it is our responsibility to do so, in order to maintain good relationships with our "other-than-human" natural relatives.

Who better to lead during this time of dramatic climate change than peoples who know or can recollect in their indigenous traditions of TK and/or TEK practices of sustainability and indigenous ingenuity—*Indigenuity*? Can you imagine a world where nature is understood as full of relatives not resources, where inalienable rights are balanced with inalienable responsibilities and where wealth itself is measured not by resource ownership and control, but by the number of good relationships we maintain in the complex and diverse life-systems of this blue green planet? I can. Read the entirety of "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions" and see if you can imagine—if you can, let's get ready for some good hard work, together.

DOI 10.1007/978-3-319-05266-3_2
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0743-2

Justice forward: Tribes, climate adaptation and responsibility

Kyle Powys Whyte

Received: 15 November 2012 / Accepted: 8 March 2013 / Published online: 3 April 2013

Abstract Federally-recognized tribes must adapt to many ecological challenges arising from climate change, from the effects of glacier retreat on the habitats of culturally significant species to how sea leave rise forces human communities to relocate. The governmental and social institutions supporting tribes in adapting to climate change are often constrained by political obstructions, raising concerns about justice. Beyond typical uses of justice, which call attention to violations of formal rights or to considerations about the degree to which some populations may have caused anthropogenic climate change, a justice framework should guide how leaders, scientists and professionals of all heritages and who work with or for federally-recognized tribes understand what actions are morally essential for supporting tribes' adaptation efforts. This paper motivates a shift to a forward-looking framework of justice. The framework situates justice within the systems of responsibilities that matter to tribes and many others, which range from webs of inter-species relationships to government-to-government partnerships. Justice is achieved when these systems of responsibilities operate in ways that support the continued flourishing of tribal communities.

1 Introduction

Concern for justice should guide how leaders, scientists and professionals who work with or for federally-recognized tribes approach climate adaptation. This diverse body of actors, which includes persons of all heritages, can affect the institutions that tribes must rely on for adaptation, from tribal natural resources departments to federal climate change programs to treaty councils. There is a tendency to invoke justice to call attention to formal wrongs against tribes, like human rights violations, or retrospective considerations, like the fact that tribes bear the hardships of anthropogenic climate change despite their relatively minimal

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

K. P. Whyte (✉)
Department of Philosophy, Michigan State University, East Lansing, MI, USA
e-mail: kwhyte@msu.edu

contributions to factors like industrial burning of fossil fuels. Yet justice also represents a crucial framework for guiding leaders, scientists and professionals in their understanding of what actions are morally essential for supporting the institutions that tribes must rely on to adapt. This paper motivates a shift from a formal and retrospective conception of justice to a forward-looking framework of justice that can begin to provide such guidance for adaptation. The framework situates justice within the systems of responsibilities that matter to tribes and many other communities. These systems range from webs of interspecies relationships to government-to-government partnerships. Justice is achieved when these systems of responsibilities operate in ways that support the continued flourishing of tribal communities. An important function of institutions like tribal natural resources departments, federal programs and treaty councils is to shelter and amend these systems in response to ecological challenges like increased frequencies of extreme weather events and changing habitats of culturally significant species.

To make this shift in how one thinks about justice, institutions and tribal adaptation, this paper lays out in Section 2 a formal and retrospective conception of justice that focuses on the constraints faced by institutions that tribes must rely on to adapt. Section 3 makes the shift to a forward-looking framework that situates justice within key systems of responsibilities. Section 4 clarifies for leaders, scientists and professionals how four policies in particular should actually be understood as systems of responsibilities that institutions can shelter and amend. They are the government-to-government relationship, the trust responsibility, the inclusion of multiple knowledge sources in climate research and the advancement of multiparty governance.

2 Formal and retrospective justice

2.1 Climate change and collective continuance

Climate change presents serious ecological challenges for tribes, which range from shifts in populations of culturally significant species to extreme weather events that may force entire human communities to relocate (Figueroa 2011; Lynn et al. 2011; Shearer 2011; Voggesser 2013; Wildcat 2009). Current research in this Special Issue paints vivid pictures of the varieties and severities of the challenges tribes face (Cochran et al. 2013; Cozzetto et al., submitted for this issue; Dittmer 2013; Gautam et al. 2013; Grah and Beaulieu 2013; Doyle et al., submitted for this issue; Voggesser et al. 2013; Lynn et al. 2013; Maldonado et al. 2013). These challenges lead many tribes to remain concerned with what I call collective continuance. *Collective continuance* is a community's capacity to be adaptive in ways sufficient for the livelihoods of its members to flourish into the future. Adaptation refers to "adjustments that populations take in response to current or predicted change" (Nelson et al. 2007, 397). The flourishing of livelihoods refers to both tribal conceptions of (1) how to contest colonial hardships, like cultural discrimination and disrespect for treaty rights, and (2) how to pursue comprehensive aims at robust living, like building cohesive societies, vibrant cultures, strong subsistence and commercial economies, and peaceful relations with a range of non-tribal neighbors, from small towns to nation states to the United Nations (UN).[1] Given (1) and (2), tribal collective continuance can be seen as a community's aptitude for making adjustments to current or predicted change in ways that contest colonial hardships and embolden comprehensive aims at robust living.[2]

[1] For a rich articulation of collective continuance as "environmental heritage," see (Figueroa 2001).
[2] Collective continuance is a concern to all communities, though this paper focuses on tribes. See Schlosberg and Carruthers (2010) for an account of Indigenous peoples and capabilities theories of justice.

Ecological challenges stemming from climate change may cause tribes to be concerned with the relationships that constitute collective continuance. Collective continuance is composed of and oriented around the many *relationships* within single communities and amid neighboring communities. The capacity to contest colonial hardships, for example, may require relationships of solidarity among community members (LaDuke 1999; Ortiz and Chino 1980) and relationships that facilitate healing and ignite spiritual awakening (Alfred 1999; Tinker 2004). It may also require building trusted networks of relationships across tribal communities who face similar hardships (Grossman 2008; Maldonado et al. 2013). The capacity to build cohesive societies, vibrant cultures and subsistence economies may require close-knit family, social and political relationships, such as elders' roles in the lives of youth, customs of child rearing and viable regimes of property rights and land use incentives (Alessa et al. 2008; Merculieff 2007; Trosper 2009). Relationships across species and with features of the land (like rivers or mountains) and ecosystems may also be required. For example, community members may uphold important relations with species like black ash tree, wild rice and sturgeon (Runstrom et al. 2002; Vennum 1988; Willow 2011). These relationships may be integral to the maintaining of multiple family, social and political relationships within the community; some species may even be the basis of clans and other important social groupings. Commercial economies require relationships that generate feasible, culturally appropriate opportunities and relationships that regulate economic production (Ranco et al. 2011; Trosper 2007). Peaceful relations with neighbors require relationships that respect the differences of each community in terms of culture, relative power, needs and capacities to exercise agency (Davis 2010; Holmes et al. 2002; Ross et al. 2010).

These types of relationships are realized through the responsibilities incumbent on the parties to the relationships. That is, to be in a relationship is to have responsibilities toward the others in the relationship. *Responsibilities* refer to the reciprocal (though not necessarily equal) attitudes and patterns of behavior that are expected *by* and *of* various parties by virtue of the different roles that each may be understood to play in a relationship. Elders may have responsibilities to mentor youth through passing on wisdom; younger generations are, in turn, responsible for learning actively from their elders. A community may have a responsibility to care for sturgeon habitat; sturgeon, in turn, may provide food and may even be expected to protect wild rice and the fishery itself. Community members may be responsible for kindling spirituality by not evaluating their fellow community members according to colonial stereotypes about Indigenous persons. Such is the mutual responsibility of honor and respect among community members. International bodies, like the UN, may have responsibilities to respect emerging norms that acknowledge the sovereignty of Indigenous peoples (Anaya 2004). These, and other similar responsibilities, are among the building blocks of collective continuance because they enable contesting colonial hardships and pursuing robust living. Tribal concern with collective continuance, then, is a concern with maintaining the capacity to be adaptive with respect to *relational responsibilities*, or all those relationships and their corresponding responsibilities that facilitate the future flourishing of tribal livelihoods.[3] I refer to relational responsibilities as *responsibilities* in the rest of the paper.

The brief examples of responsibilities provided above can be considered as belonging to larger systems of responsibilities. *Systems of responsibilities* are the actual schemes of roles and relationships that serve as the background against which particular responsibilities stand out as meaningful and binding. For example, a responsibility to maintain species habitat is part of a more comprehensive web of interspecies responsibilities that are tied to a

[3] See Cuomo 2011 for an important, and related, account of climate justice and responsibility.

community's worldview. Systems of responsibilities have intrinsic value (value for its own sake) and instrumental value (utilitarian, value for something else) for communities. For example, in Wabanaki culture berry plants have intrinsic value because they play integral roles in customs and rituals, establish the cultural status and rites of passage among Wabanaki women and are used to express relations of love (Lynn et al. 2013). Thus, an entire system of responsibilities is embedded in and permeates everything just described. The system has intrinsic value because it is essential for framing certain dimensions of Wabanaki existence. The berry plants have instrumental value because they are superfoods, according to nutritionists, having health benefits like cardiovascular protection. They also serve as cultural indicators of ecosystem services. Even systems of responsibilities amid communities have both kinds of value. For example, the government-to-government relation between the U.S. and tribes has intrinsic value because it can honor, in part, tribes' senses of nationhood. It also has instrumental value because respecting tribal sovereignty is considered to be part of effective policy formulation, implementation, and assessment.

The ecological challenges of climate change threaten collective continuance by changing the contexts in which systems of responsibilities are meaningful. Changes in landscapes may engender less opportunities for elders to teach youth in practical situations. Glacier retreat may affect the survival of salmon or start to affect the range, quality and quantity of berry resources, making it more difficult or even impossible for tribal members to exercise their responsibilities toward those species (Campbell and De Melker 2012; Lynn et al. 2013). Multiple, diverse and complex tribal needs for climate change adaptation can lead federal agencies to throw their hands in the air due to the lack of funds and personnel and lessen their efforts at honoring the government-to-government relationship. Such ecological challenges, then, put stress on the ability to perform the systems of responsibilities that are constitutive of collective continuance. Such stress threatens the intrinsic and instrumental values held by many tribes.

2.2 Institutions and collective continuance

One way that tribes have responded to the challenge of realizing and maintaining collective continuance is through the creation of or engagement with social institutions, or *institutions*. Institutions "are constellations of rules, decision-making procedures, and programs that define social practices, assign roles to the participants in such practices, and govern the interactions among the occupants of those roles" (Young et al. 1999, 3). They can range from "formal governmental institutions" and "large-scale interest-driven organizations" to various widely held beliefs, practices and norms (e.g., norms about property rights in a society) (Shockley 2012). Many kinds of institutions are in the position to affect tribes' collective continuance when faced with the ecological challenges of climate change. Such positions include, but are not limited to:

- Internal integrative adaptation planning: where tribal programs facilitate adaptation planning across multiple tribal agencies or departments, from natural resources to internal services (Mears 2012);
- External integrative adaptation planning: where such programs facilitate adaptation plans between tribal and federal partners, like the Northwest Forest Plan (Harris 2011);
- Fostering inclusive research: where such institutions participate in research processes that encompass tribal and non-tribal sciences (Hardison and Williams, submitted for this issue), like the Natural Resources Conservation Service's guide on Indigenous stewardship method (Leonetti 2010);

- Funding adaptation: where tribes can apply for grant programs that support research and education on climate change, such as the U.S. Department of Agriculture's "Agriculture and Natural Resources Science for Climate Variability and Change" challenge area;
- Networking: where cross-tribal collaboration upholds treaty areas (ceded territories), pools tribal resources or offers needed services to a range of tribes, like the Great Lakes Indian Fish and Wildlife Commission, National Congress of American Indians, National Tribal Environmental Council and the Institute of Tribal Environmental Professionals;
- Intergovernmental negotiation: where agreements with states and other subnational units are created and maintained, like the 2007 Inland Consent Decree in Michigan between a set of tribes and the state.

Institutions that are in these positions serve as resources for tribal adaptation to the ecological challenges of climate change and the pursuit of collective continuance. A tribal natural resources department, through a sturgeon or wild rice restoration program, can protect or reestablish systems of responsibilities, such as webs of interspecies relationships. A federal funding program can give tribes the support they need to engage in adaptation planning that addresses how to maintain certain systems of responsibilities when facing certain kinds of ecological challenges. A national organization or treaty council can uphold government-to-government relations with the U.S. and provide technical support for habitat monitoring. The success of these institutions has a direct impact on tribal collective continuance. Institutional success, then, can be understood as the degree to which such institutions advance tribes' collective continuance.

2.3 Coupled political obstructions and ecological challenges

The institutions that tribes must rely on to adapt to climate change are often mired in international, national and local political orders that significantly obstruct their potential for success. In this way, the ecological challenges of climate change are entangled, or *coupled*, with political obstructions. Political orders are the different circumstances of institutional interplay that can be seen as engendering opportunities and constraints on the success of particular institutions. Here, interplay refers to the field of interactions and connections among institutions. For example, U.S. politics can be seen as a national political order that involves opportunities and constraints created by the connections and interactions among institutions like laws, agency rules, judicial processes and records, available funds and spending decisions, relationships among leaders, bureaucrats and constituencies, democratic decision-making procedures and agency/departmental cultures, among many other active institutions. An institution, like a tribal natural resources department, has to navigate the landscape of these institutions to maintain legitimacy, funding and the capacity to partner meaningfully with federal agencies.

In light of this understanding, a political order can either facilitate or obstruct an institution's ability to support collective continuance. It is obstructive when institutional interplay within that political order tends to create more constraints than opportunities for the success of certain kinds of institutions. The reverse, then, is also true. A political order supports collective continuance when institutional interplay within it tends to enable opportunities for success for certain kinds of institutions.

Obstruction and support are coupled with climate change impacts when institutions that respond to climate change are involved. Federal funding programs for adaptation may be difficult for tribes to integrate across the range of tribal departments affected by climate change (Mears 2012). Tribes may be excluded from funding streams that are available to states or agencies through federal programs and/or federal budgets may be too low for tribes to engage in adaptation planning and implementation in the first place (Pardilla 2011; Suagee 2009). Tribes may also face dilemmas about whether to use bureaucratic structures (e.g., co-management and treatment as state status) acceptable to the U.S. instead of structures that flow from their own conceptions of how to govern adaptation efforts (Ranco et al. 2011). In addition, federal and state agencies may not have mature working relations with tribes conducive for climate adaptation planning and management (Shearer 2012). There may not be agencies organized to address certain kinds of problems, like relocation (Maldonado et al. 2013). States may ignore treaties and create political obstacles for tribal self-government (Nesper 2002; Silvern 1999). Different kinds of obstructions result from international climate change policies that are promulgated without Indigenous peoples like tribes having an adequate political platform from which to impact their design and evaluation (Tsosie 2010), which creates the possibility of such policies being out of sync with local circumstances and hard to implement on the ground. Though this paper focuses on federally-recognized tribes, it is important to note that state- and non-recognized tribes have access to less resources than federally-recognized tribes (hence face additional obstructions). These examples, which do not represent an exhaustive list, are obstructions because there is a burden of constraints placed on institutions that tribes rely on to assure collective continuance in response to climate change. Such constraints impose tradeoffs on tribes because they have to make harsh choices about what efforts to focus on when budgets are low, respect for tribal rights and cultures is lacking, and suitable bureaucratic channels do not exist.

These obstructions exist simultaneously at the local, national and international levels and, at times, are conjoined, making it difficult to locate an *origin* of a given set of obstructions. It may be tempting, for some, to think that the sheer complexity of these obstructions is an extremely unfortunate state of affairs for which no one is really responsible. In the next subsection, I resist this sort of thinking by arguing why obstructive political orders should be seen as part of formal and retrospective injustice against tribal collective continuance.

2.4 Injustice and responsibility

The coupled political obstructions and ecological challenges of adaptation pose significant injustice. The institutions that tribes must rely on cannot do the work of advancing collective continuance because they face more constraints than opportunities for success. In many cases, the obstructions violate tribes' social, economic and cultural human rights, as defined by the UN's International Covenant on Economic, Social and Cultural Rights (Maldonado et al. 2013), treaty rights (Dittmer 2013), subsistence rights to traditional foods (Lynn et al. 2013), as well as other rights codified by the UN Declaration on the Rights of Indigenous Peoples. These violations exemplify *formal* injustice because they infringe on or neglect recognized (formal) schedules of rights intended to protect Indigenous peoples.

Two forms of *retrospective* injustice intensify the severity of the formal injustice. First, tribes did not contribute to the creation of the obstructive political orders and have not benefited from them. The obstructions arise from colonial policies originally intended to weaken tribal resistance to the expansion of U.S. and state political institutions, private companies and private citizens over tribal territories (Wilkinson 2005). Second, while tribes have contributed to anthropogenic climate change through their farming practices that change the soil carbon content and their current uses of electricity, cars, and manufactured goods, their contributions have been relatively minimal, yet they must nonetheless shoulder the impacts via institutions embedded in obstructive political orders. These points are retrospective in considering wrongs perpetrated by past generations of people, as well as circumstances engendered unintentionally by past generations that now serve to motivate wrongs in the present.

The issue of adaptation, then, represents several formal and retrospective layers of injustice against tribes: the institutions tribes must depend on are obstructed in their capacity to uphold tribes' rights; these institutions are needed to address ecological challenges stemming from actions in which tribes participate(d) rather minimally. Yet tribes have no choice but to navigate coupled political obstructions and ecological challenges because their collective continuance is at stake. What makes this set of circumstances exemplary of injustice follows from the "double bind" (Frye 1983) such a situation presents. Tribes cannot escape having to deal with problems they largely did not bring about and there are no obvious institutional options that avoid substantial tradeoffs.

Formal and retrospective injustices should matter to people of all heritages who work with or for federally-recognized tribes. This body of actors includes researchers, planners, administrators, policy specialists, tribal liaisons, lawyers and environmental/natural resources managers in federal, state and tribal agencies and departments. It also includes policy-makers in state, federal and tribal governments, cooperative extension agents and scientists in private, public and tribal colleges and universities. Some have years of experience partnering with or working for tribes, while others have just begun such work. These leaders, scientists and professionals are also situated differently with respect to the injustices just described. Some may be the beneficiaries of colonial and industrial policies that contributed to weakening tribes and hastening climate change impacts. Others may be situated on the opposite end of this spectrum.

This body of actors cannot dismiss the injustice affecting tribes. While no one individual or agency can eliminate the injustice in question, responsibility nonetheless remains. Insofar as these leaders, scientists and professionals work with or for tribes, they are *responsible to do what is in their power* to address the coupled political obstructions and ecological challenges of adaptation. They are responsible because they do have some capacity to make changes in institutions and political orders, even if these changes must start at scales that are initially local or quite broad (such as a policy mandate that is slow to be implemented).

A problem immediately becomes clear, however, when attempting to identify exactly what this body of actors can do to better cope with formal and retrospective injustice. Recognizing injustice in tribal adaptation contexts does not aid in deciphering the range of morally essential actions that are indeed within one's power to take. A formal and retrospective account of injustice is too broad to furnish guidance, even though it often proves to be a motivation to act. As a result, simply being able to recognize that tribal adaptation contexts are rife with injustice does not furnish enough guidance for thinking about how to exercise one's responsibility to change the institutions that one can affect. It only posits how collective continuance is in peril and that something must be done, but remains silent on exactly what one should look for institutions *to do* now and in the future in relation to collective continuance.

To understand how to fulfill one's responsibility for action, there also needs to be a forward-looking account of how institutions can serve collective continuance that centers on the interaction between institutions and the systems of responsibilities that constitute collective continuance. Such an account would provide a better idea of how to structure institutions to cope with the coupled ecological challenges and political obstructions of adaptation.

3 Justice and systems of responsibilities

3.1 Justice and institutions

Coming to understand how one's actions should affect coupled ecological challenges and political obstructions requires a more specific understanding of what institutions ought to aim for in the first place. More specific actions would seem to include advocating for transformation of certain aspects of the political order, like doing what one can to ensure that tribes are treated as governments, or changing the structure of an institution to better fit the linked social, technological and natural systems that it must govern (Ebbin 2009), like taking action to strengthen an institution's jurisdiction beyond a reservation for a culturally significant species' habitat. I argue in this section for a framework of justice that explains why it is morally essential for leaders, scientists and professionals to take part in these actions. This framework of justice is not formal or retrospective, but rooted in the systems of responsibilities that constitute collective continuance.

Again, systems of responsibilities are the actual schemes of roles and relationships within and amid communities. The intrinsic and instrumental values of these systems, as held by tribes, are put in peril by climate change impacts, which compromises tribal collective continuance. *The forward-looking framework sees justice as being achieved when these systems of responsibilities operate appropriately in response to the ecological challenges of climate change.* There are three reasons supporting this view of justice. First, systems of responsibilities are sources of values that ought to be continued as such. Second, certain systems of responsibilities already have notions of justice built into them. For example, in the Anishinaabe worldview, "all beings of Creation have spirit, with duties and responsibilities to each other to ensure the continuation of Creation. Environmental justice in this context is much broader than 'impacts' on people. There are responsibilities beyond those of people that also must be fulfilled to ensure the processes of Creation will continue" (McGregor 2009, 28). Third, systems of responsibilities amid communities, such as the federal trust responsibility to tribes, should aim to realize just relations, like making sure that all affected parties participate *early* in the conception of key policy decisions. For these three reasons, justice, in many possible senses, can be achieved when systems of responsibilities are able to operate appropriately in response to the ecological challenges of climate change. This framework, then, puts systems of responsibilities at the forefront of how one thinks of justice. One's actions should be guided by goals to support appropriately operating systems of responsibilities.

While more can be said about systems of responsibilities than can be covered here, some distinctions are necessary to show how such a framework can offer guidance to leaders, scientists and professionals. Systems of responsibilities may be persisting or emerging. A system of responsibilities might be like McGregor's expression of the Anishinaabe worldview, replete with multiple responsibilities across Creation. Another example is the Wabanaki system of responsibilities as viewed from the vantage point of berry plants. These are *persisting* systems of responsibilities because they are ones that communities have traditionally relied on and seek to extend into the future as sources of intrinsic and instrumental values. Other systems of responsibility are emerging in the sense that they are adaptations to metascale forces, such as globalization, colonialism and climate change. Communities who must relocate, such as Kivalina in Alaska, are having to engender new relationships with federal and state agencies and private companies (like contractors) who are not equipped or structured to deal with climate change-motivated relocation (Maldonado et al. 2013). The need for a system of adequate responsibilities among these parties is desperately needed. Such a system would involve restructuring federal agencies, even designating a lead federal agency for relocation, creating mechanisms for Kivalina to exercise its right to self-determination in where and how it relocates, and fostering international schedules of rights specifically for communities who are displaced or who must migrate frequently in response to climate change (Maldonado et al. 2013). Thus, emerging systems of responsibilities include the new relationships that are needed for communities to relocate because of environmental change, as well as accommodate new species in their territories, cope with losses and begin to use science and other technical support as part of their collective knowledge systems,[4] among other possibilities.

The framework includes justice as connoting appropriately operating *persisting and emerging* systems of responsibilities within and amid communities. Notably, persisting and emerging systems of responsibilities are always subject to reform and transformation. For example, persisting systems of responsibilities may turn out to be harmful to the environment, or no longer safe to practice because of increased environmental hazards. Or emerging systems of responsibilities may be initially too reactionary or unreflective. Justice is situated within persisting and emerging systems of responsibilities that can also be amended. This idea is the basis of the framework that should guide leaders, scientists and professionals in their actions. Key to this framework is understanding how institutions fit within it, which I turn to now.

3.2 The function of institutions

Institutions have an important *function* regarding justice. Institutions should *shelter* and even *amend* the persisting and emerging systems of responsibilities that constitute collective continuance. Here, one must go beyond considering the position of institutions discussed in 2.2. When deciphering whether an institution encourages justice one must consider its *function* instead. The position of institutions is determined by the kind of activities they actually perform, whereas the function refers to what those activities should work to accomplish. For example, while the position of institutions suggests a range of activities from integrative planning to general partnerships (see 2.2), the function of these institutions is, as has been indicated, to support collective continuance. This means that institutions should shelter and amend the systems of responsibilities that constitute collective continuance.

Leaders, scientists and professionals are responsible for taking actions that can be shown specifically to shelter and amend these systems. Sheltering and amending are two sides of the function of institutions. Sheltering involves protecting systems from disruptions, such as coupled ecological challenges and political obstructions (2.3). Amending involves actions that improve and reform the systems themselves. Crucially, amending involves reflecting on the appropriateness of certain aspects of a system of responsibilities in light of how the environment is changing, new learning from greater experience, and new lessons from interactions with other societies. Sheltering and amending are terms that can be used to suggest more particular guidance for leaders, scientists and professionals. The justice framework described here directs this body of actors to always assess whether the actions that are in their power to perform are contributing to institutional sheltering and amending of the systems of responsibilities that constitute tribal collective continuance.

[4] See Tuana 2013 for a related conversation and key insights into gender and climate science.

4 Interpreting four policies as systems of responsibilities

4.1 Beyond compliance

Important contexts already exist in which leaders, scientists and professionals can help to shelter and amend systems of responsibilities. The contexts exist in policies that this body of actors is required to abide by, including the government-to-government relation; the federal trust responsibility; the integration of multiple knowledge sources in climate change research; and the advancement of multiparty governance. I refer to these as policies because they mandate certain kinds of action. Each of the policies has been acknowledged in U.S. laws, agency rules, treaties, reports, court decisions, guidance documents and best practices manuals; they are often part of international law and policy as well. Sometimes these policies are simply seen as legal, bureaucratic or research requirements. But each policy can be interpreted in relation to systems of responsibilities. Leaders, scientists and professionals can affect the institutions they work within to better shelter and amend these systems. These policies fit squarely within this paper's justice framework. By actively engaging with these policies, leaders, scientists and professionals can see how actions they are situated to perform can support tribal collective continuance.

4.2 Government-to-government relationship

The government-to-government relation refers to a persisting system of responsibilities amid different communities. This relation is persisting due to its origins in some of the initial encounters and agreements between Indigenous North Americans and the U.S. It is based on the idea that tribes are sovereigns—not stakeholders—alongside the sovereign U.S. government. The operation of the government-to-government relationship is intrinsically valuable insofar as it can reflect tribal national identity and instrumentally valuable because tribal governments are often in a better position to respond to climate change impacts at the local scale than any other sovereign. A major issue with this policy is that some climate change impacts may occur so rapidly that federal agencies will sidestep their responsibilities to consult tribes as sovereigns—hence threatening the values of the government-to-government relationship. Sidestepping sovereignty offsets any progress made toward a balance of power among federal and tribal sovereigns who have very different attributes (e.g., the U.S. is among the most populous and wealthiest countries in the world; most tribes have tiny populations and economies). This persisting system of responsibilities must be strong enough to withstand the abrupt and permanent impacts of climate change. Climate change impacts should not be an excuse for weakening progress toward adequate government-to-government relations. Any institution that tribes rely on for adaptation must shelter the government-to-government relationship, which means not compromising it.

4.3 Trust responsibility

The federal government has a trust responsibility to tribes. In Seminole Nation v. United States, it was claimed that "[The federal government] has charged itself with moral obligations of the highest responsibility and trust. Its conduct…should therefore be judged by the most exacting fiduciary standards" (1941, 296–297). The trust responsibility now serves as another persisting system of responsibilities amid communities, despite its paternalistic origins. It is based on the idea that tribes are inevitably tied to the forces of globalization that bind their destinies with those of other sovereigns. Its intrinsic value stems from its being a fiduciary compact; its instrumental value stems from its importance for protecting tribes against larger global forces and powers. While tribes aspire to exercise greater self-determination, they cannot pursue it without active collaboration with the federal government. Moreover, the federal government cannot fully protect all U.S. citizens and engage in cooperative federalism without genuine coordination with tribal sovereigns. The federal government has responsibilities to collaborate with tribes in their efforts to work with or resist corporations and private citizens, expand their political authority off-reservation, and pursue ecological outcomes favored by both sovereigns. Tribes are responsible for being accountable local partners. There is an inevitable interdependence of tribes and the federal government, at least in the short-term. Institutions that do not shelter the exercise of the responsibilities leave tribes in positions of greater vulnerability vis-à-vis climate change impacts that require adequate coordination with a large, cross-regional government like the U.S. federal government.

4.4 Integrating tribal and non-tribal sciences

Many policy documents in the U.S. call for the integration of traditional ecological knowledge (TEK) with science in climate change or other environmental or natural resources research. It is sometimes assumed that TEK is only instrumentally valuable to climate science because it is observational knowledge collected over generations. However, TEK best refers to a persisting system of responsibilities. McGregor, for example, defines TEK as the relations among “knowledge, people, and all Creation (the ‘natural’ world as well as the spiritual)…[it is the] process of participating (a verb) fully and responsibly in such relationships, rather than specifically as the knowledge gained from such experiences. For Aboriginal people, TEK is not just about understanding relationships, it is the relationship with Creation. TEK is something one does” (McGregor 2008, 145; see also Hardison and Williams, submitted to this issue). TEK actually refers to entire systems of responsibilities that are intrinsically valuable insofar as the systems are at the very heart of communities’ worldviews and lifeways. The inclusion of TEK in adaptation, management and stewardship strategies is actually about respecting systems of responsibilities. It means creating inclusive research practices that are not only about sharing stores of knowledge, but about sharing understanding of a host of responsibilities that should play integral roles in adaptation, management and stewardship strategies. Institutions that govern or fund research can shelter TEK systems of responsibilities by doing what it takes to ensure their robust participation well beyond the provision of accumulated observations of some landscape. More importantly, TEK concerns tribal strategies for adaptation that are based on tribal systems of responsibilities and the worldviews/cosmologies such systems flow from. Collaboration across science and TEK systems must involve conversations about how different groups of people understand the nature of reality and responsibility.

4.5 Multiparty governance

Multiparty governance refers to the policy, called for sometimes by laws or sometimes for the exercise of treaties, for greater partnership, cooperative and network institutions to address the cross-boundary, regional dimensions of climate change. They include intertribal cooperatives, conferences (summits, symposia), alliances, treaty councils, collaborations, non-governmental organizations and confederations, among others. Examples are the Columbia River Inter-tribal Fish Commission (CRITFC), The Great Lakes Tribal Climate Change Summit (2011), organized by the Menominee Nation Institute for Sustainable

Development, the United League of Indigenous Nations and The First Stewards Symposium on climate change and coastal peoples (2012). These multiparty institutions support persisting and emerging systems of responsibilities amid different tribal and non-tribal communities. Organizations like CRITFC support persisting systems of responsibilities among tribes, the federal government and states that were initially generated by treaties. Summits and symposia gather tribal and non-tribal communities together to develop new systems of responsibilities for cooperative adaptation. The intrinsic value of partnership and networking concerns the significance of strong relationships with those from different communities, from solidarity to the acknowledgment of similar spiritual grounding across communities. There is intrinsic value in developing and respecting a shared vision. The instrumental value concerns how networking and partnership provide greater political representation before state and federal governments, the collection and management of scientific data, transferable technical support and increased communication and sharing. Leaders, scientists and professionals should see specific institutions that embody this policy as sheltering persisting and emerging systems of responsibilities (of partnership and networks) amid communities.

5 Conclusion

Leaders, scientists and professionals are in the position to take justice-based action for tribes who must adapt to climate change. They are responsible for doing what is in their power to affect institutions through actions that can be shown to shelter or amend persisting and emerging systems of responsibilities. These systems of responsibilities constitute tribal collective continuance. This framework of justice offers guidance that can capture what makes certain actions morally essential for tribal adaptation. The research in this Special Issue, for example, is vital because it provides data that can contribute to sheltering systems of responsibilities involved in webs of interspecies relationships and government-to-government partnerships. The framework of justice can also be seen in work spanning from the Swinomish Climate Change Initiative to the Institute of Tribal Environmental Professionals to the Tribal Climate Change Project to the American Indian and Alaska Native Climate Change Working Group, among many other projects generated by tribes or in partnership with others that are too numerous to name here. Shifting one's thinking to seeing justice as situated within systems of responsibilities is among the key transitions that needs to occur for the sake of supporting tribal adaptation to climate change.

Acknowledgments I wish to thank the blind referees, Kristie Dotson, Becky Neher and Julie Maldonado for their dedication, time and insightful comments.

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DOI 10.1007/978-3-319-05266-3_3
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0850-0

Culture, law, risk and governance: contexts of traditional knowledge in climate change adaptation

Terry Williams · Preston Hardison

Received: 9 January 2013 / Accepted: 16 July 2013 / Published online: 15 August 2013

Abstract Traditional knowledge is increasingly recognized as valuable for adaptation to climate change, bringing scientists and indigenous peoples together to collaborate and exchange knowledge. These partnerships can benefit both researchers and indigenous peoples through mutual learning and mutual knowledge generation. Despite these benefits, most descriptions focus on the social contexts of exchange. The implications of the multiple cultural, legal, risk-benefit and governance contexts of knowledge exchange have been less recognized. The failure to consider these contexts of knowledge exchange can result in the promotion of benefits while failing to adequately address adverse consequences. The purpose of this article is to promote awareness of these issues to encourage their wider incorporation into research, policy, measures to implement free, prior and informed consent (FPIC) and the development of equitable adaptation partnerships between indigenous peoples and researchers.

1 Introduction

Indigenous peoples are increasingly recognized to possess considerable knowledge on issues related to climate change adaptation (Nakashima et al. 2012). Studies have demonstrated the value of indigenous peoples' observations of changes in climate-related weather patterns (Green and Raygorodetsky 2010), ocean phenomena (Fienup-Riordan and Rearden 2010), phenology (Egeru 2012), and fire behavior (Mason et al. 2012). Their knowledge of past ecological patterns can help reconstruct historical baselines (Thornton and Scheer 2012). Traditional ecological knowledge of ecosystem health and species distributions can contribute to culturally appropriate adaptation (Girot et al. 2011). Traditional knowledge embodied in technologies, practices and cultivated species facilitate coping with climate change (Clements et al. 2011). Traditional water-related knowledge, water harvesting and storage have allowed indigenous peoples to survive in arid lands and cope with drought for millennia (Johnston 2012).

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

T. Williams · P. Hardison (✉)
Tulalip Tribes Natural Resources Office of Treaty Rights, 6406 Marine Dr., Tulalip, WA 98271, USA
e-mail: prestonh@comcast.net

Research partnerships for using traditional knowledge and Western science for coping with and adapting to climate impacts offer benefits to both researchers and indigenous communities (Nakashima et al. 2012). Researchers benefit by acquiring a better understanding of indigenous values that need to be accommodated in adaptation planning for landscape restoration and management, traditional technologies for adaptation, and local knowledge to complement the scientific knowledge base. Indigenous communities benefit by acquiring a better understanding of climate change and its impacts and technologies for coping with these impacts that may lie outside of their traditions. Combining ways of knowing can lead to new innovations, knowledge and opportunities for adaptation through mutual learning (co-learning) and mutual knowledge generation (co-production) (Berkes 2009; Nakashima et al. 2012). Through mutually beneficial partnerships, indigenous peoples and scientists can cooperatively work to reduce climate change impacts while maintaining communities' cultural values and resources.

Despite these demonstrated benefits, concerns have been raised over potential adverse consequences of knowledge exchanges (WIPO 2012). Co-learning and co-production processes do not guarantee fairness, equal standing or address power asymmetries (Hill et al. 2012). The cultural, legal, risk-benefit and governance contexts in which knowledge exchanges occur have been under-examined. This paper will outline these contexts and suggest ways to address them. Meeting these concerns presents challenges, but these should not pose a long-term impediment to indigenous-researcher partnerships. Addressing them constitutes a significant step in recognizing their rights to resources and decision-making, reducing long-term conflicts and ensuring equitable partnerships based on free, prior and informed consent (FPIC).

2 Traditional knowledge in the context of climate change

Traditional knowledge is useful in: defining earlier environmental baselines, identifying impacts that need to be mitigated, providing observational evidence for modelling, providing technologies for adapting, and for identifying culturally appropriate values for protection from direct impacts or from the impacts of adaptation measures themselves.

In one study from the Clyde River, in Nunavut in the Canadian Arctic, scientists spent years collecting weather data (Weatherhead et al. 2010). Inuit hunters had reported significant changes in wind persistence (likelihood that wind conditions 1 day are followed by similar conditions the following day). The hunters used multiple traditional observations (lack of formation of seasonal ice crusts, changes in snow forms used as navigational aids, animal behavior and sea-ice conditions to conclude that the wind was becoming less persistent and predictable. These observations were not supported by the research station, which recorded no significant changes in wind direction or wind persistence in northeast winds (Weatherhead et al. 2010).

One explanation for the discrepancies is that the weather station was in a fixed flat area at the airport, while Inuit hunters ranged long distances in complex topographies. A significant difference was in what was that hourly measurements of mean wind intensity were limited compared to the needs of hunters who were most interested in changes in snow conditions and wind, any shift in which can mean the difference between life and death if the weather signs are misinterpreted (Weatherhead et al. 2010). Ranges of wind direction and associated sea and ice phenomena matter much more to hunters than means.

The discovery of these discrepancies has led to the establishment of more weather stations around the hunting areas which are being correlated to indigenous weather observations, as well as other projects to extend indigenous monitoring of sea-ice thickness, extent and other climate-related phenomena. Importantly, it has helped to focus research on data to support their safety and subsistence needs in a changing climate. For other relevant observations, see Nakashima et al. (2012) and Berkes (2009).

3 Cultural contexts of traditional knowledge

Although the phrase "traditional knowledge" will be used throughout this paper, the concept illustrates the kinds of problems pervasive in cross-cultural understanding and knowledge exchanges. Traditional knowledge holders themselves may not express their knowledge in this way (Berkes 2009). Traditional knowledge is a noun phrase, turning knowledge into an object. Traditional knowledge holders commonly think of knowledge as a contextualized process connected to dynamic, evolving relationships expressed in the phrase "ways of knowing" (Berkes 2009).

In a widely influential definition, Berkes has characterized traditional ecological knowledge (TEK) as "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes 2012). This definition frames TEK within a materialistic, evolutionary framework that does not always conform to the beliefs of the knowledge-holders themselves, who may refer their knowledge as living breath, coming directly from the spirit world, ancestors, dreams, or conversations with plants, trees, rocks or other aspects of a living and spiritual nature (Little Bear 2000). Referring to a "cumulative body of knowledge" appeals to Western concepts of trial-and-error learning. While indigenous peoples are concerned deeply with relationships between humans and the natural world, this definition and many discussions focus on material concept of relationships (i.e. species interactions, social-ecological system interactions) and leave the spiritual dimensions out as metaphysical constructs. These so-called constructs are often at the core of indigenous identity and underpin their beliefs and practices, and ignoring them can create significant impediments to equitable partnerships (Burkett 2013).

Some have proposed dichotomous representations of traditional and Western scientific knowledge systems (Berkes 1993). These have limitations, however, as there is a spectrum of both indigenous and scientific ways of knowing with many areas of overlap (Berkes 2009). Both provide ways of knowing about and acting on the world to reliably achieve desired outcomes.

Differences remain in the way indigenous peoples conceive of intangible values and relationships. Scientists commonly aim to produce validated and transportable knowledge objects that are held to be universally true and objective regardless of cultural background. The scientific ethic is generally to make knowledge widely available[1]. This may be contrasted with traditional ways of knowing which are place-based, localized, and may carry prescriptions related to their use (Kipuri 2009). Indigenous peoples often believe their knowledge has spiritual origins and powers, and employ it to communicate with the spirit world to create outcomes in this world (Kipuri 2009).

Traditional knowledge has been described as being shared freely in a commons (Amankwah 2007), or as un-owned by peoples without property concepts (Helfer and Austin 2011). This has been countered by studies that demonstrate traditional ways of

[1] For example, the Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities (2003) http://oa.mpg.de/lang/en-uk/berlin-prozess/berliner-erklarung/

knowing occur in a wide spectrum of beliefs, norms, institutions and ways of owning that includes property concepts (Carpenter et al. 2009). Thom and Bain (2004) describe many ways in which aboriginal individuals and groups in Canada are the holders, custodians or owners of rights, powers, property and responsibilities. They hold proprietary interests in rituals, private professional knowledge, songs, stories, magic words, dances, shamanic knowledge, fishing sites and myriad other aspects of tribal life. Some weather knowledge may be shared widely, but may also be held by weather shamans holding proprietary knowledge and practices and passing these down through families (e.g., Chumash Indians of California, Timbrook 1987).

Traditional knowledge is regulated by customary norms and embedded in a web of relationships defining who may use it, when it may be used, appropriate uses, and the rituals, words or practices that must accompany its use (Thom and Bain 2004). When traditional knowledge is shared, it is often accompanied by stewardship obligations within communities with expectations that outsiders also carry these obligations when knowledge is shared. This creates significant challenges in terms of the foreign contexts to which it is exposed when conveyed outside community boundaries.

4 Legal contexts of traditional knowledge

Once traditional knowledge is shared outside of a community, it enters alien social and legal contexts. Natural scientists often emphasize the value of partnerships with indigenous communities in outcomes-oriented terms. Social science researchers commonly use political, social or moral/ethical frameworks. These approaches emphasize the social aspects of knowledge holder-researcher relationships, promoting reciprocity, respect and protocols for them (Hardison and Bannister 2011). Although a significant advance, these approaches have rarely addressed the legal contexts of these exchanges.

Traditional knowledge holders will often evaluate seekers of knowledge to ensure they have the proper attitudes, maturity and responsibility to receive such knowledge (Noble 2009; Thom and Bain 2004). Once the knowledge has been shared with persons outside of the community, they may in turn share it with third parties who have not agreed to respect social conventions and are not bound by law to do so. Without special legal measures to recognize stewardship obligations associated with the knowledge, it becomes subject to foreign norms and laws that generally automatically apply regardless of the intentions of either the communities or the researchers (Riley 2005). Despite good intentions, protocols and best practices, the exchanged knowledge is not governed by customary laws or community aspirations, but by foreign laws such as intellectual property, freedom of expression, public domain and common heritage of mankind.

Countries have begun to put into place laws that protect such transfers of traditional knowledge to third parties. Under the Nagoya Protocol to the Convention on Biological Diversity, seekers of traditional knowledge related to genetic resources must first obtain the prior informed consent (PIC) of indigenous and local communities. The World Intellectual Property Organization (WIPO) is negotiating a potential international treaty to regulate international access to genetic resources, traditional knowledge and folklore (now referred to as traditional cultural expressions).[2] A number of countries have passed national laws against appropriation and unfair use (McManis and Terán 2011).

[2] Traditional Knowledge, Genetic Resources and Traditional Cultural Expressions/Folklore http://www.wipo.int/tk/en/

However, these measures fall short of fully recognizing and respecting the values, beliefs and customary laws of the traditional knowledge holders themselves. Traditional knowledge is widely treated as secular knowledge and brought into conformation with existing national and international laws. We will not cover these in detail, but will focus on copyright law as a primary example of the conflict between customary law and non-indigenous law, then briefly mention other legal conflicts that require attention. It is important to understand the basics of these laws in order to appreciate the current limitations of social contracts in ensuring respectful partnerships.

4.1 Intellectual property laws

4.1.1 Copyrights

A copyright is a grant of a temporary monopoly by a government to provide economic incentives to individuals or firms for innovation. Copyright law defines a public domain from which people can freely draw, composed of knowledge that is too old to be protected and once protected knowledge that has exceeded the term of protection. Traditional knowledge is often treated as being in the public domain because it is too old to be protected, it is orally expressed rather than written down ("fixation requirement")[3], and it cannot be attributed to a specific author. Once published or shared, traditional knowledge immediately starts its journey into the public domain where all of the traditional norms, beliefs or customary laws associated with it are stripped away. It becomes available to anyone with no legal requirement to obtain permission, share in any benefits or observe stewardship obligations for its use.

One aspect of copyright is the "fact/expression" dichotomy. Only the particular expressions in written works are protected, not the underlying ideas which become immediately available for exploitation (Bannister 2004). One example is the Traditional Knowledge World Bank (TKWB) project, a database of traditional knowledge for mitigating desertification and adapting to climate change.[4] The project intends to support "protection of traditional knowledge rights that can be implemented by persons, communities, disseminators and traditional technique innovators,"[5] without indicating how these rights are identified and distinguished from traditional knowledge in the public domain, or how the policy has been implemented in deciding on entries into the database. The project owns the copyright for the descriptions of the traditional adaptation technologies in the database, not the original knowledge holders. The underlying technologies are not protected and may be freely used by anyone.

Copyright law grants fair use exemptions allowing access for research, education, news reporting, parody, commentary and civic deliberation without requiring permission of the copyright holder. These exemptions are fundamental to the functioning of scientific and academic research, but they may not respect indigenous customs. Water rituals, for example, are a common response by indigenous peoples to climate- and weather-related water problems (AIPP 2012). In reviewing publications that recognize relationships between water, heritage, identity and worldviews, one author notes "religious beliefs and customs are often the focus, and examples are often illustrated by photographs of religious festivals or rituals that contribute to conservation of water or demonstrate the intimate spiritual relations people have with water"

[3] Copyright generally requires that works be written down, or fixed, in order to receive protection. A few legal systems are beginning to recognize some protection for orally transmitted knowledge.
[4] Traditional Knowledge World Bank, http://www.tkwb.org/
[5] http://www.tkwb.org/web/?page_id=4

(Hiwasaki 2012). While such recognition is positive, some cultures believe that publication of photographs of sacred ceremonies interferes with their spiritual power and/or triggers adverse spiritual and physical consequences (e.g. Tsosie 2007).

In the absence of intangible cultural heritage laws, copyright law is automatically applied to any shared traditional knowledge and offers few legal safeguards that allow indigenous peoples to have their traditions respected or to gain benefits from the use of their knowledge.

4.2 Non-intellectual property laws: freedom of information Act (USA) / freedom of expression / the common heritage of humankind

Non-intellectual property laws may also serves as impediments to sharing traditional knowledge. Because of a Supreme Court decision in 2001 (Department of Interior v. Klamath Water Users Protective Assn), tribes cannot share sensitive knowledge or information privately with the US on a government-to-government basis, because any exchanges are subject to Freedom of Information Act (FOIA) requests (Doremus and Tarlock 2008).

Disclosed traditional knowledge may also be subjected to claims for use under the right to freedom of expression. Collective customary laws can impose durable restrictions on the use of certain knowledge, practices and symbols, which do not become open to use by others because they have been publicly shared. Current freedom of expression law favors an individual interpretation to justify access to traditional knowledge against customary laws, norms and beliefs (Fletcher 2012; Riley 2007).

The Common Heritage of Mankind asserts that because certain resources are important to humanity as a whole, they should be protected beyond potentially the more narrow concerns of individual sovereign nation states (Curci 2010). Framing intangible cultural heritage as part of the common heritage of humankind can take away governance, ownership and control by indigenous peoples in the name of humanity (Coombe 2009).

Caution should be taken when framing the exchange of traditional knowledge within the social discourses of voluntary guidelines, protocols, partnerships and agreements. Knowledge exchanges occur within powerful and compelling legal frameworks that often conflict with and take precedence over social arrangements. Stewardship obligations generally have no equivalent in national and international legal systems. Social aims for respectful partnerships may be difficult to achieve without changes in legal systems to accommodate indigenous concepts and ways of being.

5 Risk contexts of traditional knowledge

A third consideration rests on arguments related to the manner in which sharing decisions are made, which should be based on free, prior and informed consent (FPIC). This concept is contained in the Declaration on the Rights of Indigenous Peoples (UNDRIP) and in decisions of the Convention on Biological Diversity and the Nagoya Protocol as prior informed consent (PIC).

5.1 Free, Prior and Informed Consent (FPIC)

FPIC is used in UNDRIP to create procedural safeguards for decision-making by indigenous peoples. FPIC ensures that when they are approached with proposals for access to their lands, resources or traditional knowledge, they are provided with all necessary and appropriate information they deem necessary to make an informed decision (FSC 2012). The concept is an extension of informed consent used in medicine, in which doctors have a duty not only inform patients of potential benefits of a procedure or treatment, but also of all relevant risks, and can only proceed with patient consent.

The concepts of FPIC can be understood to mean:

Free The decision must not be coerced or biased. In UNDRIP it emphasizes that decisions should be free from external manipulation, interference and coercion. "Free" has also been used in the Indigenous Peoples Rights Act of 1997 (Republic Act No. 8371) of the Philippines to add the meaning of "determined in accordance with their respective customary laws and practices." The word thus emphasizes freedom to determine the process of decision-making and freedom from coercion.

Prior The term is often described as consent being required prior to access. This may be clear in terms of access to material resources. It is less clear case of traditional knowledge, which may have been disclosed in the past or appear in hybrid forms with other forms of knowledge. UNDRIP holds that permission is required prior to use, even if it has been disclosed, consistent with much customary law.

Consent Consent is usually applied to a legally competent individual, corporate entity or competent authority of a government. In regard to indigenous peoples, decision-making authority may be less clear. There is a wide diversity of social and political organization among indigenous communities. Tribes and First Nations in the US and Canada are organized into governments that have the authority to make decisions, but difficulties may arise because of conflicts of authority between political authorities and the traditional knowledge holders.

Exercising the right to consent creates an obligation on the knowledge holders to establish authoritative decision-making processes. The institutionalization of authoritative processes, while challenging, should decrease conflicts over the long-term.

Indigenous peoples have argued that consent should be applied to both access to undisclosed knowledge or use of already disclosed knowledge. This implies a due diligence requirement to discover potential holders and owners of already disclosed knowledge before putting it into use. It also suggests that researchers need to clarify the pathways by which traditional knowledge is incorporated into research. Clarifying the cultural, legal and ethical dimensions of these pathways and formal mechanisms of consent is a major task of efforts to incorporate traditional knowledge into adaptation decision-making.

Informed This provision holds that indigenous communities must be provided with all necessary relevant information of benefits, costs and risks sufficient to make an informed decision. There are as yet no standards on how to implement this, although there are some emerging attempts (FSC 2012).

To implement this, a traditional knowledge sharing risk assessment should be prepared in collaboration with the traditional knowledge holders, taking into account cultural, legal and governance contexts. Climate adaptation projects often extoll benefits without addressing the potential risks of knowledge sharing, as in two otherwise admirable attempts to survey existing experience, *Advance Guard* (McLean 2010) and *Weathering Uncertainty* (Nakashima et al. 2012).

Such considerations may have little effect on decisions to exchange knowledge. Traditional knowledge related to observations of changes in phenology, ice-out dates, coastal currents, fire behavior or hydrological patterns may carry few risks when shared. Other kinds of traditional knowledge carry more risks, either through moral hazards related to cultural values or through misuse that can seriously threaten indigenous livelihoods and cultural sustainability. Risks and benefits are linked to specific values held by the knowledge holders, to external legal and social environments and to the characteristics of the resources to which the knowledge is bound. Traditional knowledge is not generally about abstract things, but more focused on relationships and activities that constitute a way of life (Berkes 2012), and these can be harmed by misuse.

Below is an example that illustrates the kind of reasoning that can be applied and indicates where more research is needed to develop FPIC guidance in climate change adaptation (Fig. 1).

5.2 Risks of sharing climate-relevant traditional knowledge in the coast Salish

The Coast Salish of the Pacific Northwest live on small territories surrounded by much larger populations with different traditions and values, which increases conflicts over use of resources. Tribes have retained rights to wild resources on off-reservation lands to which they have little control. These uncultivated resources are sensitive to external drivers such as climate change, invasive species, species range shifts, habitat fragmentation and human population growth. Life history characteristics of wild species such as mobility and rarity can exacerbate problems in their governability (characteristics of resources that make them

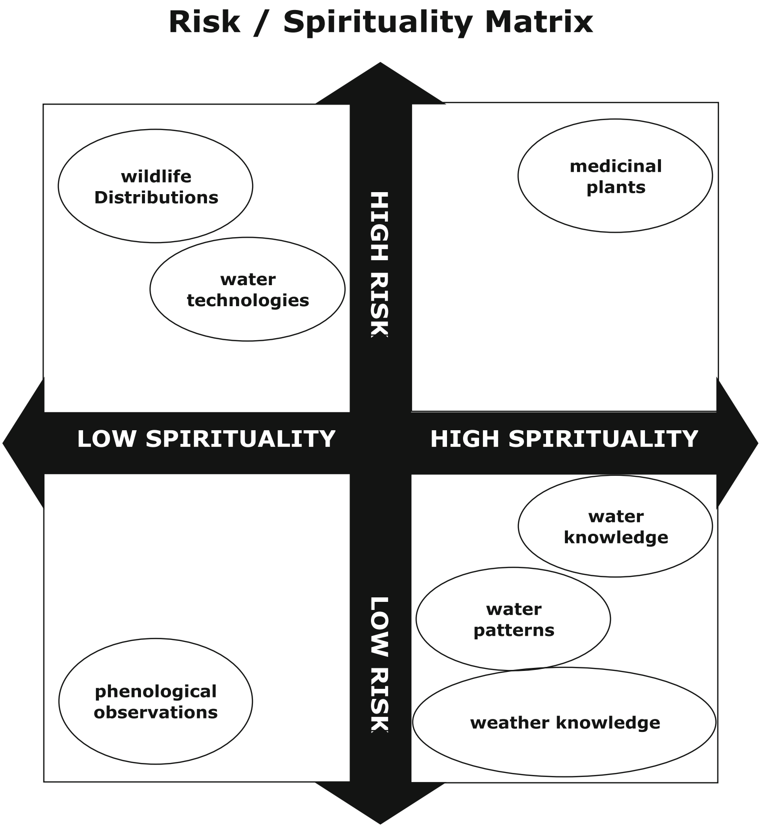

Fig. 1 Matrix illustrating hypothetical trade-offs between types of traditional knowledge with differing levels of spiritual significance and risks related to sharing. Risks include cultural values (moral hazard), material harms (misappropriation and overharvesting) and lack of benefit sharing

more or less manageable) and governance (characteristics of institutions, norms, laws and policies for their management) relative to cultured species. Coast Salish elders already complain they can no longer access many traditional foods because of overharvesting (Richards and Alexander 2006). Under these conditions, there may be few options for risk spreading through knowledge sharing.

Climate adaptation can be enhanced by traditional knowledge of wildlife movements and concentrations, for which tribal hunters have considerable knowledge (Huntington 2000). Even without cultural sensitivities to sharing, there are risks to publicly revealing the locations of valuable game. These risks can be amplified where tribes have low control over access to game in off-reservation situations.

Disclosing knowledge of medicinal plants useful for addressing climate change impacts on health carries the risks of use against cultural traditions and overharvesting. The bark of the Pacific yew is used for healing wounds by several Pacific Northwest tribes (Moerman 1998), The development of the anti-cancer drug taxol from bark extracts lead to illegal overharvesting in which trees were killed by stripping them entirely, endangering the yew (Laird and Wynberg 2008; Wynberg et al. 2009).

These challenges do not pose an insurmountable barrier to respectful knowledge exchanges. The changes from past practices will likely involve uncertainty and conflicts at first, but will reduce them in the long-run. Exercising the right to FPIC creates a duty to sort out processes for authoritative decision-making. Building respect for traditional knowledge and FPIC through professional training, public education, the development and implementation of guidelines and policies and other measures are necessary to reduce conflict over time (Hardison and Bannister 2011).

Under indigenously-led FPIC, many traditional knowledge exchanges related to climate change are likely to continue where they present few risks and provide benefits to indigenous peoples. The examples emphasize the need for precaution in ensuring their values and rights are protected both against the impacts of climate change and adaptation measures that fail to accommodate their rights and values.

6 Traditional knowledge governance

The combined arguments suggest that traditional knowledge exchanges in adaptation partnerships cannot be viewed as unproblematic information exchanges, and potentially carry significant risks as well as benefits and opportunities. Some knowledge useful to adaptation cannot be shared because it is too sacred, risky to disclose or weakly protected from appropriation and misuse. The dilemma often facing indigenous peoples is to either disclose their knowledge and lose control of it, or fail to have their values reflected and protected from climate impacts in adaptation measures. One pathway for resolving this dilemma is through viewing traditional knowledge exchanges through a governance mechanism, as opposed to a voluntary social framework.

Traditional knowledge held by indigenous peoples has significant political or governance dimensions in addition to cultural, legal and risk dimensions. Indigenous peoples are a subject of international law as being a distinct group with a distinct bundle of rights, which they hold as peoples with the right of self-determination (Anaya 2009). While their status as peoples is not universally recognized by all countries, it is affirmed by the United Nations Declaration on the Rights of Indigenous Peoples (2007).

Peoples have the right of self-determination to freely determine their political status and form of governance within their territories (Anaya 2009). Self-determined governments have the inherent authority to grant and make trade-offs between the rights of their citizens, but not the rights of the citizens of other sovereigns. Sovereigns work through diplomacy and treaty making to gain cross-recognition for transboundary issues. The number of states that recognize the right to self-determination and self-governance is growing (Anaya 2009).

The Supreme Court has ruled that the tribes' sovereign status is not granted to them by the United States, but an original right reserved by them in the treaties.[6] This reserved rights doctrine holds that any right not explicitly ceded by treaty is retained as a sovereign right. Consequently, tribal treaties are not legally interpreted as a listing of all rights that are retained, but primarily as a listing of those that are ceded. Any right not explicitly ceded is retained (Pevar 2012). The US has a government-to-government relationship with tribes in which tribes have retained inherent sovereign powers. Traditional knowledge holders are therefore not one stakeholder group among others. The United States Constitution, policy and law recognize them as members of sovereign governments that have retained inherent rights to determine their own laws and constitute their own cultural arrangements and institutions.

Tribal treaties have the fundamental purpose of allowing tribes to freely determine their ways of life in return for the cession of vast amounts of land. Tribes often reserved off-reservation rights to fish, hunt, trap and gather because their ancestors understood that their reservations would be insufficient to maintain their ways of life (Goodman 2000). Indigenous peoples have often expressed that their knowledge is inextricably linked to their lands, waters and heritage as inalienable and permanently associated with their identity and territories through ancestral, material and spiritual relationships (Carpenter et al. 2010; Kipuri 2009).

Official US policy affirms that tribes have sovereign rights "to protect tribal cultural heritage and cultural identity expressed in both tangible and intangible forms." [7] Therefore, in the United States it is well-established in Constitutional law and national policy that the tribes have retained unextinguished sovereign jurisdiction over their tangible and intangible cultural heritage. Traditional knowledge is fundamental to the purpose of the treaties and a component of the governance rights reserved in them.

Article 31 of UNDRIP affirms the similar right of indigenous peoples "to maintain, control, protect and develop their cultural heritage, traditional knowledge and traditional cultural expressions, as well as the manifestations of their sciences, technologies and cultures." Although many nations view UNDRIP to be aspirational and not currently legally binding, all signatories have committed themselves to moving towards implementing its principles. The Nagoya Protocol of the Convention on Biological Diversity recognizes the obligation to obtain the prior informed consent of indigenous and local communities prior to accessing and using their knowledge.

In the case of indigenous traditional knowledge, scientists therefore may not be dealing with knowledge and resources held by one stakeholder among many whose rights can be balanced, but with knowledge held collectively by a political entity that has the right of self-determination and self-governance. Concepts, instruments and approaches for stakeholder processes are inadequate when addressing issues related to sovereign property, which are dealt with through treaties, bilateral agreements and other government-to-government instruments.

In those cases where traditional knowledge is held by those with governance rights, it is governed by its own rules and laws determined by its proper sovereign, which do not

[6] United States v. Winans, 198 U.S. 371 (1905)

[7] Undated letter from David J. Hayes, Deputy Secretary of the Interior to the Tulalip Tribes, received 28 September, 2011 and available from the corresponding author.

necessarily resemble the laws of other sovereigns. While indigenous sovereigns cannot directly impose these rules and laws on citizens of other sovereigns, they can expect that equitable relationships can be worked out for cross-recognition of their issues based on comity guiding peaceful relations among states, respect for their human rights, and federal fiduciary obligations to respect their rights (Smith 2010). These rights are not limited to treaty tribes, but are increasingly recognized as a general right of indigenous peoples in international law, national constitutions and national legislation (Tsosie 2013).

Under conditions of sovereignty, governments may elect to engage in co-management or self-management of their resources and heritage (Goodman 2000; Nie 2008). In this case, co-management refers to a situation in which sovereign powers have equal status in determining an outcome related to shared sovereign resources. One sovereign cannot unilaterally impose their will on another, and equitable outcomes must be found in mutually agreed terms. Many cases of issues related to adaptation to climate change may involve both traditional knowledge and its associated biocultural heritage. In the classic model, federal scientists might request access to traditional knowledge to assess its validity and applicability to managing resources on the federal landscape. In a co-management and self-management model, indigenous peoples are recognized to have governance rights over their biocultural heritage, including tangible forms (resources) and intangible forms (traditional knowledge), both on their territories and in specified external areas.

Useful and unproblematic knowledge exchanges can occur without involving traditional knowledge. Where traditional knowledge is needed, solving management problems may not require its transfer, allowing indigenous peoples to apply their knowledge by themselves to their own biocultural heritage using negotiated outcomes that are mutually agreeable to the sovereigns (Davidson-Hunt et al. 2012). This performance-oriented approach allows the knowledge to be retained by the knowledge holders while upholding standards for public accountability in the management of resources.

Many traditional knowledge studies have framed indigenous peoples as stakeholders and have not treated traditional knowledge as a governed, sovereign property. Governance rights over traditional knowledge are not separable from governance rights over the biocultural heritage to which they are associated. This is not to argue that traditional knowledge exchanges should not occur, but their rights of governance should be taken seriously, respected and accommodated in resolving issues. The guiding principle is that exchanges should be based on free, prior and informed consent and mutually agreed terms based on equal standing.

7 Respect for indigenous governance in a climate change context

An example of using traditional knowledge in a respectful manner for climate change adaptation comes from the Waswanipi Cree in Northern Quebec through the Ndhoho Itschee Process (Trosper et al. 2012). They are interested in documenting their traditional forest knowledge in order to enter into respectful stewardship agreements to promote climate change adaptation and appropriate forest management on traditional lands not under their direct control. They do not believe they can convey their complex knowledge and values to others for management on their behalf, but want their stewardship role acknowledged. Communities are producing detailed community "family maps" which detail past, present and future desired land use. These maps are not shared outside the community. The maps are used to prepare a map of conservation values, which are shared with the government and industry for use in collaborative planning processes. In this way, they retain and manage sensitive cultural knowledge internally, while making available proxy values useful for climate change adaptation and resource scenario building.

A review of 21 case studies of natural resources management in Australia resulted in a classification of resource management initiatives as indigenous governed collaborations, indigenous-driven co-governance, agency-driven co-governance and agency governance (Hill et al. 2012). They concluded that “indigenous-driven co-governance provides better prospects for integration of IEK and western science for sustainability of social-ecological systems” than agency-driven co-governance and agency governance. They stress the importance of processes that support indigenous governance and do not vest power in government agencies but instead distribute decision making in “wider networks of families and communities” (Hill et al. 2012).

Berkes suggests there are limits to the extent to which science and traditional knowledge can be combined (Berkes 2009), concluding “the two kinds of knowledge should not be blended or synthesised; both should retain its own integrity” as they have their own epitemologies based on different worldviews. “Not taking knowledge out of its cultural context is one of the biggest challenges of indigenous knowledge research” (Berkes 2009).

8 Conclusion

This review raises issues beyond the narrow context of the exchange of information useful for solving climate-related problems. The exchange of traditional knowledge involves cultural values, multiple legal jurisdictions, risks to cultural sustainability and survival and rights to self-governance. Indigenous peoples are engaging in adaptation projects and knowledge exchanges, and these are leading many documented benefits. Despite these documented benefits, it must be kept in mind they are being invited to mobilize traditional knowledge, often deeply spiritual and core to their identity, to solve large-scale problems they cannot avoid and that are not of their making.

Traditional knowledge and associated biocultural heritage are often already threatened by drivers of global climate change such as population growth, urban sprawl, excessive consumption and land conversion. The consequences of disclosing valuable knowledge can add to these pressures. Indigenous peoples may be wary of sharing because of a history of exploitation, a lack of recognition and respect for their values and rights, a lack of safeguards for the control and proper use of their knowledge and associated biocultural heritage and by a lack of perceived long-term benefits to themselves for sharing. Partnership arrangements without proper safeguards may be encourage them to disclose relatively unprotected knowledge associated with relatively unprotected resources. Knowledge sharing and learning from one another will be critical for finding just and lasting solutions to the climate crisis. As indigenous peoples are some of those least responsible and most threatened by climate impacts, it is the highest duty of those seeking access to their knowledge and resources to ensure they are not further harmed and that their rights in cultural values are fully respected.

These arguments have focused on accommodating indigenous peoples and protection of traditional knowledge. While indigenous peoples wish to keep some of their gifts to themselves, it is clear many also wish to share some of them in the spirit of mutualism and reciprocal accommodation. The earth system is in decline and the indigenous concept of stewardship obligations is a good starting point for healing.

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DOI 10.1007/978-3-319-05266-3_4
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0736-1

The impacts of climate change on tribal traditional foods

Kathy Lynn · John Daigle · Jennie Hoffman · Frank Lake · Natalie Michelle · Darren Ranco · Carson Viles · Garrit Voggesser · Paul Williams

Received: 15 November 2012 / Accepted: 4 March 2013 / Published online: 26 March 2013

Abstract American Indian and Alaska Native tribes are uniquely affected by climate change. Indigenous peoples have depended on a wide variety of native fungi, plant and animal species for food, medicine, ceremonies, community and economic health for countless generations. Climate change stands to impact the species and ecosystems that constitute

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

K. Lynn (✉)
Adjunct Research Faculty, Environmental Studies Program, University of Oregon,
5223 University of Oregon, Eugene, OR 97403-5223, USA
e-mail: kathy@uoregon.edu

J. Daigle
School of Forest Resources, 221 Nutting Hall, University of Maine, Orono, ME 04469-5755, USA

J. Hoffman
EcoAdapt and Jennie Hoffman Research and Consulting, 4755 NE Lamms Lane, Poulsbo,
WA 98370, USA
e-mail: hoffrau@gmail.com

F. Lake
USDA Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002, USA
e-mail: franklake@fs.fed.us

N. Michelle
Graduate Student, University of Maine, Orono, ME 04469, USA

D. Ranco
Department of Anthropology, University of Maine, 5773 S. Stevens Hall, Orono, ME 04469-5773, USA

C. Viles
Undergraduate Student, University of Oregon, 5223 University of Oregon, Eugene, OR 97403-5223, USA

G. Voggesser
Tribal Partnerships Program, National Wildlife Federation, 2995 Baseline Road, Suite 300, Boulder,
CO 80302, USA

P. Williams
Suquamish Indian Tribe, PO Box 498, Suquamish, WA 98392, USA
e-mail: pwilliams@suquamish.nsn.us

tribal traditional foods that are vital to tribal culture, economy and traditional ways of life. This paper examines the impacts of climate change on tribal traditional foods by providing cultural context for the importance of traditional foods to tribal culture, recognizing that tribal access to traditional food resources is strongly influenced by the legal and regulatory relationship with the federal government, and examining the multi-faceted relationship that tribes have with places, ecological processes and species. Tribal participation in local, regional and national climate change adaption strategies, with a focus on food-based resources, can inform and strengthen the ability of both tribes and other governmental resource managers to address and adapt to climate change impacts.

1 Introduction

American Indian and Alaska Native tribes face unique and disproportionate challenges from climate change that are not yet widely understood in academic or policy arenas. This paper explores one of these challenges in particular—the impact of climate change on traditional foods and the reality that 1) tribal access to resources is strongly influenced by the legal and regulatory relationship that tribes have with the federal government (Whyte 2013), and 2) tribes have a unique and multi-faceted relationship with places, ecological processes, and species. These frameworks shape tribal responses to climate change.

Indigenous peoples have depended on a wide variety of native fungi, plant and animal species for food, medicine, ceremonies, community and economic health for countless generations. Water is held sacred by many indigenous peoples (Cozzetto et al., submitted for this issue), and considered by some to be a traditional food (Jones et al. 2008; Colombi 2009). In combination with other stressors, climate change may affect tribes' relationships with traditional foods, including access, availability, harvesting strategies, and ability to store, process, and use foods in traditional ways.

The availability of all types of traditional foods (hunted, fished, gathered, and cultivated) has greatly diminished as ecosystems and water resources have been exploited or converted to other uses. The productivity of remaining ecosystems may be impacted by a variety of factors including disease, pollution, invasive species and management actions. Climate change can impact ecosystems and lifecycle processes in complex ways. For example, tribal harvesters have noticed shifts in harvest times for traditional foods; if the timing of flowering plants and the presence of pollinators, such as birds and insects, become less synchronized, impacts can ripple throughout the food webs.

The relationship between tribal culture and species, habitats, and ecosystems is integral to understanding the impacts of climate change on indigenous communities. Reciprocity—respect for and responsibility to—wildlife and natural resources is embedded in indigenous cultures. Reciprocal relationships are fundamental to how tribes will respond to climate impacts (Whyte 2013). The effects of climate change on traditional foods take place in the context of a host of other changes, both the ecological stressors commonly cited in climate change literature and the rapid cultural, economic, and political changes experienced by indigenous communities globally and by tribes in the United States since the arrival of Europeans (Parrotta and Agnoletti 2012). While this article focuses on indigenous peoples within the United States, these impacts are being experienced by indigenous peoples around the world (Maldonado et al. 2013).

This article seeks to illustrate some of the ways in which climate impacts on traditional foods may affect tribal cultures and traditional ways of life. To accomplish this, the article explores the cultural context for climate change impacts on traditional foods for Alaska Native and American Indian tribes, as well as the impacts of climate change on tribes' access to, use of, and relationship with traditional foods. The article also examines historical and contemporary examples of tribal adaptation that may inform strategies to address climate impacts on traditional foods in the future.

2 Cultural context: understanding the impacts of climate change on traditional foods

The indigenous relationship between food and people is intimately tied to the cultural, physical, emotional, psychological, and spiritual health of tribal communities. The impacts of climate change on particular species or ecological processes, therefore, are directly connected to climate impacts on tribal culture and the importance that traditional foods have for tribes. This section is intended to build an understanding of the impacts climate change may have on tribal culture. This is accomplished by describing indigenous relationships with traditional foods broadly, and providing an example of what traditional foods (e.g., berry plants) mean to the Wabanaki people as way of understanding the potential for climate change to affect tribal culture and traditional ways of life.

Tribes have long historical, cultural, and physical connections to plants and wildlife. These relationships manifest themselves in their connections to and reliance on traditional foods. These bonds form the basis of traditional ecological knowledge (TEK), the indigenous way of knowing (Williams and Hardison, submitted for this issue). TEK, established over countless generations of interactions with the natural world, provides a powerful roadmap to ensuring the sustainability of traditional foods. Simultaneously, TEK and tribal connection to traditional foods offer strategies for adaptation that can help tribal and non-tribal resource managers confront the climate challenge. As TEK informs research, tribes and non-tribal entities can work together to incorporate TEK in a tribally-appropriate manner (Williams and Hardison, submitted for this issue.)

Approximately 1.14 million (~22 %) of American Indians and Alaska Natives live on or near reservations (Norris et al. 2012), and many pursue lifestyles with a mix of traditional subsistence and commercial harvesting activities . Traditional foods such as fish, game, nuts, fungi, berries, algae, greens, roots, water and seafood provide not only sustenance, but also cultural connections through storytelling, ceremonies, harvesting, processing, and sharing of food resources. Many tribes strive to maintain a strong, diversified traditional diet and food-related traditions, but are experiencing barriers such as poverty, and changes in ecosystem quality and species distribution instigated by pollution, urbanization, policy restrictions to traditional food access, cultural assimilation and climate change, (Jernigan et al. 2012; Kuhnlein and Receveur 1996; Norgaard 2005; Verbrugge 2010).

Climate change impacts on ecological processes, habitat quality, and species populations present a growing threat to traditional food use. Tribes are experiencing declines in health that accompany traditional food use declines. Obesity, diabetes and cancer, rare in communities living on a traditional diet, are now increasing health problems in tribes across the U.S. (Boyce et al. 1993; DeGonzague et al. 1999; Kuhnlein and Receveur 1996; Norgaard 2005; Ravussin et al. 1994; Teufel 1996; Kuhnlein et al. 2009). For example, the majority of Karuk people today, whose homeland stretches along the middle Klamath River in California, have experienced an almost complete elimination of two traditional staples from their historical daily diet: salmonids (*Oncorhynchus* sp.) and acorns (*Notholithocarpus* and *Quercus* sp.). These foods made up 50 % of a traditional Karuk diet. Accompanying this loss are skyrocketing rates of diabetes (21 % of the population) and heart disease (40 % of the population) (Norgaard 2005).

The loss of opportunity to gather traditional foods in tribal communities is resulting in the denial of their rights to have access to a steady supply of nutritionally balanced, culturally relevant foods (Conti 2006; Jernigan et al. 2012; Power 2008). Additionally, the preservation and maintenance of traditional knowledge and associated subsistence practices that accompany food acquisition are threatened. As traditional foods are affected by climate change through habitat alterations and changes in the abundance and distribution of species, there is a resulting erosion of traditional practices and knowledge (Kuhnlein and Receveur 1996; Nabhan 2010).

2.1 Indigenous people, berry plants, and climate change

To demonstrate a cultural context for considering climate impacts on traditional foods, we explore the multi-faceted relationship between berries and indigenous peoples in the Northeast. Traditional ecological knowledge about particular berry plant species encompasses the holistic aspects of wellness and includes physical, emotional, psychological and spiritual realms of the individual and community. These beliefs are reinforced by the traditional value systems of responsibility, respect, reciprocity, relationship, and reverence that are imbedded within many cultural customs and rituals. Despite the challenges of cultural loss, incomplete transmission of knowledge related to subsistence skills, and fewer opportunities for learning traditional lifeways from elders, many traditional practices are still employed in indigenous cultures. Today, as a result of economic conditions, subsistence practices and food acquisition are paramount for those who rely on hunting, fishing, trapping and berry harvesting.

Scientists have only begun to understand the importance of berry plants as food medicine in Native American cultures (Burns Kraft et al. 2008). Recent investigations have identified diverse phytochemicals in berries that act to prevent a wide range of metabolic syndromes and chronic disease outcomes (Seeram 2008). Current studies show significant improvement in cardiovascular protection and the biological parameters of metabolic syndromes, such as hyperglycemia, hyperlipidemia, hypertension and lipid peroxidation that are significant to native populations (Basu et al. 2010).

The common berry plants used by the Wabanaki people (the Penobscot, Passamaquoddy, Micmac, and Maliseet Indian Nations) include the familiar blackberries (*Rubus allegheniensis* & *R. canadensis*), raspberries (*Rubus occidentalis* & *R. idaeus*), blueberries (*Vaccunuim angustifolium* & *V. corymbosum*), cranberries (*Vaccinium macrocappon* & *V. oxycoccos*), and strawberries (*Fragaria x ananasa*), as well as less familiar indigenous berries like shadberry (*Amelanchier alnifolia*), chokecherry (*Prunus virginiana*), high bush cranberry (*Viburnum trilobum*), elderberry (*Sambucus nigra*), and gooseberry (*Ribes uva-crispa*). Today, nutrition experts consider these berries "superfoods" based on their bio-chemical content and biological and physiological functions (Seeram 2008).

Wild berry plants serve a number of utilitarian, nutritional, medicinal, and spiritual purposes among the Wabanaki people. The berry fruits are not the only portion of the plant that is essential as food-medicine to the Wabanaki, for certain species the whole plant is utilized. The season, age of the plant (maturation stage), use (i.e. food or medicine), traditional teachings and ceremonies dictate which portion of the plant should be harvested, prepared, and administered.

Berries serve as key cultural indicators of ecosystem services in Wabanaki culture. The shadberry (or serviceberry) is a well-known commodity among the Wabanaki people. In early spring, the blossoming of the shadbush coincided with the arrival of the spring migration of the shad fish and acted as a signal for the people to move to the low lands (Frink and Dow 2005).

Berry plants are also extremely important for Wabanaki women. Recovery of the traditional uses of these plants has been on the rise in the younger generations of

Wabanaki society over the past 20 years (Michelle 2012). The native women are returning to the traditional uses of berry plants for health, well-being, and spirituality. The strawberry represents a primary nutrient source for female reproductive development and the psycho-social behavior of the young adolescent female. The "Strawberry Ceremony" or "berry fast" is still used for female adolescents' initiation into womanhood. The traditional medicinal uses of berries and certain portions of the plant strengthen women's reproductive organs and act as the primary medicine for endocrine system balancing, reproductive toning, birthing preparation, post-partum bleeding and toning as well as a preventive for post-partum infections and uses during menopause (Cook 1996; Michelle 2012). Women also use berries for treating cyst formation in the reproductive organs. The Wabanaki continue to use sweet berries such as strawberries, raspberries, and blueberries to express love for each other and their children and these berries are often shared among the clans for use during sacred rituals.

Climate and other environmental changes are starting to affect the range, quality, and quantity of Wabanaki berry resources (Michelle 2012), as well as having impacts on these resources in other places such as Alaska (Kellogg et al. 2010). Wabanaki Nations in Maine and Canada are struggling to protect and preserve living cultural resources, such as berries. Pre-existing stressors, including dwindling territory, pollution, declining health services and ongoing assimilation policies are affecting access to and availability of cultural species, such as berries. As climate change adds to the impacts on berry plant use and access, tribal health and well-being will be under even greater threat.

3 Climate impacts on traditional foods

Native species and indigenous peoples' use of them are attuned to particular climates and ecosystems. Climate change will affect these balances, throwing ecosystems and traditional foods into disarray. Climate-related changes can exacerbate the impacts of existing stressors or conditions on species and ecosystems. These impacts to individuals, populations, and habitat quality will result in reverberating changes in food webs and the valued food species tribes utilize. This section explores a range of climate-related impacts on traditional foods, as well as discussion about the related impacts to tribal culture and traditional ways of life.

In the Pacific West, Columbia Plateau climate change threatens a multitude of ecosystems that provide traditional foods for tribal communities. Wild food resources such as huckleberries, are valued by many groups, and are addressed by broad scale climate adaptation strategies. However, these strategies may not consider many tribal traditional foods. Non-forested environments deemed "unproductive" by non-indigenous cultures often contain important tribal traditional foods. Such tribally valued bulbs and roots include: onions (*Allium* sp.), camas (*Camassia* sp.), brodiaea (*Brodiea* sp., *Dichelostemma*, *Triteleia* sp.), lilies (*Lilium* sp., *Calochortus* sp.), and lomatiums (*Lomatium* sp.) (Hunn 1990). Tribal efforts to amplify attention to these foods are increasing public and land manager cooperation in planning to preserve and restore components of these landscapes. In coastal Louisiana, tribes are beginning to see declines in traditional food resources as a result of land loss, saltwater intrusion and disruption of estuaries from increased storm activity (PNW TCCP 2012). Athabascan peoples in central Alaska are experiencing changes in moose habitat. Moose are an important staple food and the decline in moose has put stress on peoples' traditional diets. In addition to changes in where moose range, hunters have noticed that moose seem to appear less healthy (Daigle and Putnam 2009). Winter sea ice area is diminishing rapidly due to climate change, and the loss of this habitat is hurting Pacific walrus populations, which directly threatens Alaskan traditional food security (Verbrugge 2010; IPCC 2007a; NRC 2010a).

Climate change impacts on water temperature and availability (see Cozzetto et al., submitted for this issue) will also have significant impacts on tribal traditional foods. Already, the lack of water is among one of the leading causes for the decline in the ability to grow corn and other crops (Lobell et al. 2008; NRC 2010a; Redsteer et al. 2010). Corn has been central to many native cultures, particularly Puebloan people in the Southwest and the use of corn pollen is central to every Navajo ceremony. In the Great Lakes region, warming winters and changes in water level are crippling the ability of wild rice to grow and thrive in its traditional range. Wild rice is a pillar of cultural health for the Anishnaabeg people, and any decline in wild rice negatively affects their well-being (Minnesota 2008). In response to threats facing wild rice, the Fond du Lac Band of Lake Superior Tribe has begun trying to address potential hydrological changes. In the early 1900s, settlers built ditches to drain the land for agricultural purposes, resulting in negative impacts to the watershed. The Fond du Lac are now building dams at ditch flow points to keep water levels stable and prevent extreme changes in water level that would negatively affect wild rice harvests (Hoene 2010).

Climate change is thought to be posing significant threats to salmon (Mote et al. 2003, Dittmer 2013; Grah and Beaulieu 2013; Beechie et al. 2012). Salmon is central to the lives of many indigenous peoples, providing spiritual, physical and cultural well-being (Dittmer 2013). Over the past two centuries, overharvest, habitat degradation, urbanization, and water diversion for a variety of human uses have led to dramatic declines in salmon populations (Mote et al. 2003), with profound effects on the peoples whose lives and cultures are intertwined with them. For some tribes, the loss was rapid and absolute: in the last few years, the Colville Tribes lost access to both salmon and their traditional fishing grounds following the construction of the Grand Coulee Dam on the Columbia River and the filling of the reservoir behind it (McKay and Renk 2002). Now, the rapidity of climate change may be exacerbating existing stressors and creating new ones, including extremes in stream flows and water temperatures that limit the survival of salmon fry (Mantua et al. 2010).

Already, projections indicate that salmon populations throughout the Puget Sound, in the Pacific Northwest, are expected to decline considerably as water temperatures warm (CPR 2011). The changing climate can also broaden the geographic range of disease organisms, increasing threats to salmon and other species. In Alaska, the Yukon River and its tributaries, for example, Chinook salmon are now commonly infected with a single-celled parasite previously unknown in Alaskan salmon (Kocan et al. 2004). Articles in this issue explore the impacts of climate change on salmon and tribal culture in greater detail (Dittmer 2013; Grah and Beaulieu 2013).

Shellfish have been an integral part of the culture, economy and diet of coastal peoples for millennia. Historically, along the Pacific Coast, many tribes actively maintained “clam gardens” by moving rocks to create berms and terraces (Anderson and Parker 2009). Climate change threatens this resource in multiple ways including increases in surface temperatures, sea level rise and changes in ocean chemistry (e.g., temperature, pH, dissolved oxygen, and nutrient concentrations) and circulation patterns (IPCC 2007a, b; NRC 2010b; Feely et al. 2012). These changes could affect every stage in the life cycles of shellfish and finfish.

Sea level rise will inundate existing shellfish beds. The intertidal ecosystem provides habitat, food, and refuge for hundreds of species, including forage fish, juvenile salmon, crab, eel grass, algae, clams and humans. Human response to storm damage (the manifestation of sea level rise) is typically to build more resilient infrastructure. This effectively cuts off the supply of sediments to beaches and prevents the shift of intertidal ecosystems landward—the natural response to sea level rise. In the conflict between allowing coastal habitat shift and maintaining space for land-based needs, the land-base needs often win. In more industrialized areas, sea level rise and storm surge may inundate sources of pollutants on land and wash them out to near shore areas, contaminating shellfish beds. Indeed, the National Oceanic and Atmospheric Administration's Damage Assessment, Remediation, and Restoration Program has created an online tool specifically geared towards incorporating interactive effects of climate change and contaminants in coastal protection and restoration in Puget Sound (Industrial Economics and Research Planning 2011).

Increasing air and water temperatures are also having negative impacts on marine life. Because warmer conditions affect mussels differently, warmer conditions over the past 50 years have led to a 51 % decrease in the vertical extent of mussels along the Strait of Juan de Fuca and southern Vancouver Island, with populations disappearing entirely in the warmer parts of this region (Harley 2011). Warmer water temperatures are also creating conditions more favorable for the phytoplankton and bacteria that cause paralytic shellfish poisoning, amnesiac shellfish poisoning, and a range of other illnesses (Trainer et al. 2003).

Ocean acidification is a tremendous threat to aquatic ecosystems and the billions of people who rely on protein from the world's oceans. One of its many effects is to corrode the calcium carbonate shells of shellfish, a group that includes many of the species that form the base of the aquatic food chain (IPCC 2007b; Kleypas 2006; NRC 2010b; Feely et al. 2012). One-third of the carbon dioxide from anthropogenic sources is absorbed into the oceans (Sabine et al. 2004). This limits the rate of global climate change, but at the cost of altering the fundamental chemistry of the oceans (Orr et al. 2005; Kleypas et al. 2006; WA Blue Ribbon 2012).

4 Tribal adaptation in a changing environment

4.1 Historic tribal approaches to adaptation

Indigenous peoples have adapted to environmental conditions since time immemorial. Through observations of wildlife foraging and the harvesting and processing of foods, tribes refined their traditional ecological knowledge (TEK) of when, where, and how animals, plants, algae and fungi could be used as food. The extent of tribal TEK about different types of foods and corresponding ecosystems or habitats reflect millennia of experiences with changes in climate (Blukis Onat 2002; Huntington and Fox 2005). In this section, we explore how historic tribal adaptation to climate and ecosystem changes may inform tribal adaptation to climate change today. We also provide examples of contemporary tribal approaches to climate change adaptation.

Climate and ecosystems change over time. Paleoclimate, archaeology, and ethnoecological research provide a foundation for understanding how climate, environmental productivity and tribal food utilization strategies evolved. Historical evidence demonstrates the rate of climatic change experienced within past environments and the accompanying tribal food security systems that occurred in response to these changes (Moss et al. 2007). Although the rate of change experienced was not as rapid as contemporary conditions, tribes historically experienced significant climate changes that affected ecosystems (Moss et al. 2007) and food-based resources, requiring tribal cultures to strategically adapt and respond to survive (Meltzer 1999; Newsome et al. 2004).

Throughout these historic changes, indigenous peoples maintained access to many traditional foods. Tribal cultures developed sophisticated socio-economic and technological systems to access, acquire, process and store foods (Anderson and Parker 2009). In the Pacific Northwest, archaeological evidence suggests remarkably stable use of salmon over the past 7,500 years despite broad regional climatic stressors that reduced salmon populations and habitat quality (Campbell and Butler 2010). The key to this resilience is found in strong, multifaceted connections to the resources used, adaptive resource management, and beliefs and social institutions that kept salmon harvest within sustainable levels (Campbell and Butler 2010).

Traditional knowledge of ecological processes provides some insight into how climate change may impact traditional foods. However, limited access to the fraction of traditional territories, the competition tribes face when gathering, the ongoing impacts of colonization and urbanization, and the current state of environmental degradation pose significant threats to tribes' ability to maintain the progress they have made to maintain tribal health and traditional ways of life.

4.2 Informing contemporary adaptation strategies

Historic and cultural factors can inform how tribal adaptation to climate change may occur. Cultural attributes that aid tribes in adaptation include their relationship of respect and reciprocity that binds nature and harvester together as illustrated in the example of Wabanaki peoples and berry plants. As such, culture and TEK may guide the myriad of social, political, ecological and cultural adaptation strategies that tribes may pursue. Socio-political mechanisms include compelling federal agencies to clarify their legal obligations under the treaties and to implement those federal policies at the local level. Tribes may enter government-to-government agreements to increase their role in local resource management, to access additional areas to gather traditional foods, or lease and buy lands that ensure sustained access to traditional foods. Tribes may also exchange information and identify different technologies to access, acquire, process, and store foods. Additionally, tribes can develop formal and informal agreements with other tribes to grant or request access to traditional foods that may now only be found on one of their reservations. Tribes may have to consider diversifying their food-based resources and possibly adopting and utilizing new animals, plants, or fungi.

Addressing climate change through the knowledge, experiences, and policy contexts of indigenous peoples provides a powerful counter-point to the lack of effective global climate responses. As indigenous peoples may experience some of the harshest impacts of climate change, they can also lead the way in creative solutions for adaptation and ethical policy strategies. As part of the Arctic Climate Impact Assessment, the six permanent Arctic Indigenous peoples' organizations of the Arctic Council put forward a list of recommendations for the world to consider as part of our global response to climate change. These include, among other recommendations, bringing indigenous "views, perspectives, and recommendations to international institutions mandated to combat the impacts and effects of global climate change," and "acknowledging their authority to protect and promote their ways of life" (Watt-Cloutier et al. 2004). These suggestions clearly focus on more local approaches to climate change policy that treats indigenous peoples and TEK as not just data points to prove a larger trend, but as vital contributions to addressing climate change in an equitable manner.

A more localized example of tribal adaptation comes from the Confederated Tribes of the Umatilla Indian Reservation's (CTUIR) innovative partnership with local, state and federal entities. In 2006, in an effort to protect traditional foods (referred to as "First Foods" by the CTUIR), the CTUIR Department of Natural Resources adopted and implemented the First Foods mission. Based on the First Foods ceremonies and practices of the CTUIR, this mission provides an indigenous framework for restoring ecosystems that support culturally important foods. First Foods assessments are expected to inform future research questions, protection and restoration strategies, and policy development. Beyond restoring native habitats and protecting tribally-valued food resources, the mission also emphasizes the critical importance of tribal member access to their First Foods (Jones et al. 2008).

Also in the Pacific Northwest, tribes are working with government and non-governmental organizations to restore access to and the habitat of tribally-valued food resources (Eckart 2012; White 2004). Changes in fire regimes, land management tenures, and public versus tribal values, have reduced access to and the quality of habitats that formally supported traditional foods. For example, in the Cascade Mountains of Oregon, the Confederated Tribes of Siletz Indians and the USDA Forest Service - Willamette National Forest are working together to enhance and restore huckleberries and camas roots. Hazardous fuels reduction and forest thinning treatments are being utilized to reduce tree competition and shading on huckleberries. Meadow restoration is facilitating access to and increases in the vigor of camas and other tribally-valued plants species, promoting tribal subsistence activities. These larger interconnected landscape forests and meadow treatments are thought to foster ecosystem resilience against the effects of detrimental wildfires and climate change (Paul 2010).

These examples demonstrate the ability of tribes to engage directly with federal partners to develop and implement adaptation strategies aimed at preserving tribal access to traditional foods.

5 Conclusion

Climate change impacts on tribal traditional foods should be viewed in the context of historical and cultural tribal relationships with places, wildlife, and plants, as well as in the landscape of the treaties, federal policies, and federal trust responsibilities and regulations in which they exist (Whyte 2013). Moreover, tribes view climate change adaptation in light of their reciprocal relations to care for and respect natural resources (Whyte 2013). As a result of these relationships of reciprocity and responsibility between tribes and nature and existing policies, Indian tribes' vulnerability to climate change, and the adaptation strategies they adopt are multi-faceted and deeply rooted in a complex historical context. As sovereign governments, tribes have the authority to identify and implement adaptation strategies, and attempt to influence and strengthen the climate change protocols of other governments.

The various adaptive practices tribal practitioners and communities employ may enable managers to institute changes in policies, regional strategies, and resource regulation/ conservation that enable ecosystems to respond more favorably to climate change. Tribal participation in local, regional and national climate change adaption frameworks and strategies, with a focus on food-based resources, can assist with prioritizing research and management directions.

Under extreme and rapid conditions of severe change at different ecological scales (AMS 2012), western scientists and managers may need to partner with tribal scientists, managers, harvesters, and communities to explore innovative approaches to addressing climate change impacts. Tribal participation in climate change research, policy development and planning can help identify more solutions that fully consider tribal cultural values. Climate change will not obey the jurisdictional boundaries between tribal, private, state, and federal lands. As such, meaningful government-to-government relationships and collaboration will be vital to address the climate change impacts to the traditional foods, and to the wildlife, plants, and habitats valued by tribes and other Americans.

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DOI 10.1007/978-3-319-05266-3_5
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0735-2

Indigenous frameworks for observing and responding to climate change in Alaska

Patricia Cochran · Orville H. Huntington · Caleb Pungowiyi · Stanley Tom · F. Stuart Chapin III · Henry P. Huntington · Nancy G. Maynard · Sarah F. Trainor

Received: 13 November 2012 / Accepted: 3 March 2013 / Published online: 26 March 2013

Abstract Despite a keen awareness of climate change, northern Indigenous Peoples have had limited participation in climate-change science due to limited access, power imbalances, and differences in worldview. A western science emphasis on *facts* and an indigenous emphasis on *relationships* to spiritual and biophysical components indicate important but distinct contributions that each knowledge system can make. Indigenous communities are experiencing widespread thawing of permafrost and coastal erosion exacerbated by loss of protective sea ice. These climate-induced changes threaten village infrastructure, water

Caleb Pungowiyi is deceased; Inuit leader/hunter.

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

P. Cochran
Alaska Native Science Commission, P.O. Box 244305, Anchorage, AK 99524, USA

O. H. Huntington
Wildlife and Parks, Tanana Chiefs Conference, 122 1st Avenue, Ste 600, Fairbanks, AK 99701, USA

C. Pungowiyi
Savoonga, AK, USA

S. Tom
Newtok Village Council, P.O. Box 5545, Newtok, AK 99559, USA

F. S. Chapin III (✉)
Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775, USA
e-mail: terry.chapin@alaska.edu

H. P. Huntington
23834 Clearing Drive, Eagle River, AK 99577, USA

N. G. Maynard
Cryospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

S. F. Trainor
Alaska Center for Climate Assessment and Policy, University of Alaska Fairbanks, Fairbanks, AK 99775, USA

supplies, health, and safety. Climate-induced habitat changes associated with loss of sea ice and with landscape drying and extensive wildfires interact with northern development to bring both economic opportunities and environmental impacts. A multi-pronged approach to broadening indigenous participation in climate-change research should: 1) engage communities in designing climate-change solutions; 2) create an environment of mutual respect for multiple ways of knowing; 3) directly assist communities in achieving their adaptation goals; 4) promote partnerships that foster effective climate solutions from both western and indigenous perspectives; and 5) foster regional and international networking to share climate solutions.

1 Introduction

> "Not that long ago the water was far from our village and could not be easily seen from our homes. Today the weather is changing and is slowly taking away our village. Our boardwalks are warped, some of our buildings tilt, the land is sinking and falling away, and the water is close to our homes. The infrastructure that supports our village is compromised and affecting the health and well-being of our community members, especially our children" (Village of Newtok) (ADCCED 2012)

Air temperatures in Alaska are increasing twice as fast as the global average. This has led to a shrinkage of summer sea ice, a shortening of the snow-covered season, warming and thawing of permafrost, which together have altered the structure and functioning of northern ecosystems, including their human and non-human residents. These facts are well documented (ACIA 2005; IPCC 2007), but what are the consequences for the people who live there?

Although most Alaskans live in cities, the majority of the land area is sparsely populated by a largely indigenous population living in small communities with no road access and no connection to the electrical grid. Excluding the oil-rich North Slope, rural Alaska is the most extensive area of poverty in the United States, in terms of household income, yet has the highest costs of fuel and other commercial goods because of the physical isolation of these communities (e.g., $7–12 per gallon for fuel). In addition, few jobs are available to provide a cash income. Given these stark economic realities, indigenous people in rural Alaska depend directly on the local environment for food, transportation, and survival and have a strong need to understand and manage the consequences of climate change.

However, this is nothing new. Indigenous Alaskans have lived off the land and sea for thousands of years with minimal connection to the global economy. Over the millennia indigenous people have developed a traditional knowledge that allowed survival, and often thriving, in the landscapes and seascapes of the North (Langdon 1986; Huntington and Watson 2012). Moreover, the weather, environment, and plant and animal populations are so variable, both seasonally and among years, that indigenous people have developed skills to cope with a wide range of conditions. Given the close connections between indigenous people and environment and the rapid environmental changes occurring in Alaska, Alaska Natives are well poised to observe climate change, understand its ecological and societal consequences (Krupnik and Jolly 2002), and develop potential response strategies (Voggesser et al. 2013).

Despite a keen awareness of climate change, northern indigenous peoples have not played a central role in national and international assessments of climate change. To the extent that indigenous issues are considered, assessments have been largely *about* indigenous people, not *by* them. This reflects, in part, a rejection by western science of indigenous worldviews that integrate spiritual, biophysical, and cultural dimensions of reality. In this paper we briefly (1) summarize some elements of indigenous worldviews that are important in understanding their potential to contribute to climate-change solutions, (2) present examples of the impacts of climate change on indigenous communities, and (3) suggest a path forward that will enhance the capacity of indigenous peoples to contribute to and benefit from climate-change research.

2 Traditional knowledge as a lens for observing climate change

Although indigenous understandings of climate change are as diverse as the many environments and cultures in which they are situated, there are some common features and differences compared to western science. Respect for elders and the natural environment, for example, are commonly held community values, and traditional stories of biophysical and spiritual ties between people and nature reflect these values across most of Alaska's indigenous cultures, despite important cultural and environmental differences in the specific ways in which people interact with their environment (ANSC 2003–04; ANKN 2012). Many elements of indigenous worldviews are embedded in a holistic framework that connects the land to the air and water, the earth to the sky, the plants to the animals, the people to the spirit (Deloria and Wildcat 2001; Wildcat 2009). This perspective recognizes Earth as a coupled social-biophysical system in which all things are connected (Levin 1999), so it is not surprising to many arctic residents that arctic changes exert important feedbacks to the Earth System (ACIA 2005; IPCC 2007). Following from this holistic framework, Alaskan indigenous perspectives often emphasize relationships between people and other living and non-living entities ("how to"), whereas western science tends to emphasize facts ("what is"). Traditional ways of knowing therefore provide an ethical framework that can guide adaptation to current and emerging conditions (Huntington and Watson 2012). Given these important differences between western and indigenous worldviews, it important not to attempt to merge them into a single framework but to recognize respectfully what each has to offer in solving the challenges faced by modern society (Huntington 2000a; Huntington et al. 2005; Huntington and Watson 2012).

Native cultures and sense of identity are directly tied to the places where people have lived for generations through observations, riddles, stories, dances, art, language, music, and traditions (Wildcat 2001; Huntington and Watson 2012). Since each cultural element evolved in a climatic and ecological context, it is vulnerable when climate alters that context and as elder knowledge-keepers pass away. In addition, plants and animals in these places are viewed as relatives that share the world—not as resources to be exploited (Morrow and Hensel 1992; Wildcat 2009). This strong sense of place and sense of connection to the organisms that inhabit this place makes climate change a much deeper and more personal impact than in communities that view the environment primarily as a place to live, work, and extract resources (Huntington et al. 2006).

3 Climate-change impacts on Alaskan indigenous communities

Hunters from indigenous communities frequently speak of the thinning sea and river ice that makes harvest of wild foods more dangerous (Ford and Furgal 2009; Loring and Gerlach 2010; McNeeley and Shulski 2011; Moerlein and Carothers 2012), changes to permafrost that alter spring run-off patterns, changes in seasonality of vegetation and animal movements

(McNeeley and Shulski 2011), a northward shift in seal and fish species, and rising sea levels with more extreme tidal fluctuations (Krupnik and Jolly 2002; Downing and Cuerrier 2011; Davis 2012; McNeeley 2012; University of Alaska Fairbanks 2012). These and other indigenous observations indicate a widespread awareness that climate is changing in ways that were not anticipated based on traditional knowledge. Although western and indigenous observers often make similar observations, the context for interpreting their significance frequently differs. In the words of the late Caleb Pungowiyi, an Indigenous Elder from Savoonga, Alaska (quoted in Eamer et al. 2007):

> "As we think about the future and where these trends may lead us, we wonder what alternatives are available to Native villages in Alaska and elsewhere in the Arctic. If marine mammal populations are no longer available or accessible to our communities, what can replace them? In the Great Famine, there were no alternatives to the food provided by hunting and fishing. Today, there are stores with food and other resources that can be harvested. A gradual change might give us time to adjust, but a sudden shift might catch us unprepared and cause great hardship. We need to think about the overall effects on marine mammals and other resources. Some may adjust, but others will not. Our ancestors taught us that the Arctic environment is not constant, and that some years are harder than others. But they taught us that hard years are followed by times of greater abundance and celebration. As we have found with other aspects of our culture's ancestral wisdom, modern changes, not of our doing, make us wonder when the good years will return."

In the remainder of this section we emphasize climate changes that have greatest impacts on indigenous communities. Problems intrinsic to many rural Alaskan communities, such as the failure or lack of adequate drinking water systems, sanitary sewage disposal, and usable landfills, are magnified by climate change (Alessa et al. 2008; Brubaker et al. 2011b; Doyle et al. submitted for this issue). Thawing of permafrost beneath lakes and ponds that provide drinking water, for example, cause water-security challenges (Alessa et al. 2008), and deteriorating water and sewage systems increase the risk of skin and respiratory infections (Gessner 2008; Hennessy et al. 2008). Warming may bring new diseases to the Arctic through diseases in harvested foods (McLaughlin et al. 2005; Virginia and Yalowitz 2011) or through northward-moving insect and vertebrate vectors (Parkinson and Evengård 2009), such as the northward movement of giardiasis in beaver that follow the climate-induced expansion of shrubs in western Alaska.

Ice cellars traditionally used for storing food are thawing, causing food contamination illnesses and loss of traditional foods (Alessa et al. 2008; Brubaker et al. 2011a). In some communities residents are seeking new methods to store food or are shifting from a traditional to a western diet (Brubaker et al. 2009; Moerlein and Carothers 2012), which increases dependence on non-traditional, expensive, and often less-healthy store-bought foods (Ford 2009; Loring and Gerlach 2010). Climate-induced impacts on arctic peoples interact with contaminants, such as POPs (persistent organic pollutants) and heavy metals, many of which are concentrated at high latitudes (AMAP 2009). Local concerns about contaminants sometimes contribute to the shift in diet away from traditional foods. This is associated with increases in "modern diseases" such as obesity, diabetes, cardiovascular disease, and cancer (Ford 2009; Parkinson 2010) and contributes to negative social, cultural, economic, and nutritional effects (Weller 2005; Redsteer et al. this issue).

Climate change has significantly altered both terrestrial and marine habitats and therefore the opportunities for hunting and fishing, which are important both nutritionally and culturally (Huntington et al. 2005). Reductions in winter sea ice reduce habitat for walrus and seals, which are a critical component of people's diet in northwest Alaska. In addition, the thinner, less stable sea and river ice is a significant safety hazard for hunters (Laidler et al. 2009) and can disrupt the timing and dependability of subsistence economies (Ford and Furgal 2009; Gearheard et al. 2010). On the other hand, a shorter ice-season expands the time available to hunt from boats. The net effect of climate change on subsistence probably depends on context.

Most (86 %) Alaskan indigenous villages are affected to some extent by flooding and erosion: "While the problems are long-standing, various studies indicate that coastal villages are becoming more susceptible to flooding and erosion due in part to rising temperatures" (GAO 2003). Newtok, a Yupik Eskimo village in western Alaska, and other coastal communities experiencing accelerated rates of erosion caused by the combination of thawing permafrost, decreased arctic sea ice, and autumn storms that now occur during the ice-free season. As a result of these geophysical changes, the community has lost critical basic infrastructure, and storms are a continuing threat to life and property. Although the community has sought for a generation (17 years) to relocate, the stipulations of current federal and state statutes and regulations, such as the post-disaster recovery legislation, have impeded their efforts (Bronen 2011; Maldonado et al. 2013).

On land, the major impacts of climate change have been changes in temperatures, snow, ice, weather, seasonality, permafrost thaw, and wildfire. Increased evapotranspiration and declining river discharge reduce opportunities for barge delivery of fuel and increase the cost of living in remote villages (Kofinas et al. 2010). The ecological and hydrological changes related to permafrost degradation are changing the habitats, migration patterns, and distribution of species that are important for fishing and hunting ; (Kofinas et al. 2010; Loring and Gerlach 2010; Voggesser et al. 2013).

The frequency and severity of wildfire in the Interior are expected to continue increasing with climate warming and will likely result in increased fire suppression near communities, which may provide economic opportunities through the deployment of local fire fighting crews (Trainor et al. 2009). However, increased severity and annual extent of area burned will increase risk to life and property, alter hunting opportunities, and likely increase both physical and mental health effects from wildfire smoke. Lichens, which are a key winter food for caribou, require 70 years to recover after wildfire, whereas moose increase in abundance within a few years (Chapin et al. 2008; Nelson et al. 2008).

4 Interactions of climate change and development

Development activities in the Arctic (e.g., oil and gas, minerals, tourism, and shipping) are of interest to indigenous communities, because of both perceived threats and anticipated benefits (Kruse 1991; Huntington et al. 2007; Maynard et al. 2011). The retreat of summer sea ice removes a major barrier to access to much of the Arctic, as can be seen in the transit of the Northern Sea Route by cargo ships and the Northwest Passage by cruise ships (AMSA 2009). Greater levels of industrial activity across the Arctic are expected to alter the distribution of species, disrupt subsistence activities, increase the risk of oil spills, and create various social impacts (Baffrey and Huntington 2010; Maynard et al. 2011). Oil and gas development as well as mining activities have already impacted some major populations of Eurasian reindeer herds and the associated indigenous herder communities in Northern Russia and Norway (Maynard et al. 2011). At the same time, development provides economic opportunities, if it can be harnessed appropriately (Kruse 1991; Kruse et al. 2004; Baffrey and Huntington 2010). For indigenous peoples in Alaska, a major question is how such activities will be managed and by whom, and how such management will take account of the impacts of climate change (Huntington et al. 2012). There are often strong differences of opinion within and among communities about how to balance development with traditional lifeways. To the extent that development can help pay for climate impact prevention and mitigation, there are potential benefits, albeit at the cost of accepting more industrial development. Here as elsewhere, community futures will depend in large part on the degree to which communities are empowered to make or influence the decisions that will affect them.

5 Preparing for the future

In this paper, we have shown that indigenous Alaskans have extensively documented patterns and processes of climate change and its impacts on ecosystems and human communities. How can indigenous peoples contribute more effectively to understanding and adapting to climate change? We suggest a multi-pronged approach:

1. *Engage communities in designing climate-change solutions*. Regional Advisory Councils, comprised largely of indigenous hunters from rural Alaska, can provide advice to the Alaska Board of Game about adjustments in hunting seasons needed to account for climate change-induced changes in seasonality (McNeeley 2012). A recent shift in decision-making authority from the politically appointed Board of Game to the Subsistence Division of the Alaska Department of Fish and Game should make these decisions about hunting regulations more responsive to local observations and needs. In other cases, adaptation solutions are constrained more by economics and competing ways to earn a living (e.g., summer construction vs. subsistence harvest) than by regulations. For example, declines in sea ice and stronger winds often produce earlier and larger open-water leads during the spring whaling season, requiring larger boats for safe navigation and whaling (Krupnik 2002). At the same time, later fall freeze-up has allowed hunters on St. Lawrence Island to pursue bowhead whales in November and December, providing a new opportunity for hunting that can help offset some of the difficulties in spring (Noongwook et al. 2007), an innovation made possible by a lack of seasonal restrictions on whaling activity. The Alaska Native Science Commission, the University of Alaska Fairbanks and four Alaskan indigenous communities (Igiugig, Koyukuk, Newtok, and Nikolai) recently initiated a Community Partnership for Self-Reliance and Sustainability. The goal of the partnership is to develop a collaboration that implements each community's own vision for self-reliance and sustainability, based on potential solutions chosen by communities and implemented with assistance from the university and agencies. Each community had at least one issue that differed from issues faced by the other three communities, was critical to community self-reliance, and was not addressed by any government program. This included funding for village relocation in Newtok, acceptance of Koyukuk's strategy of adapting to flooding by protecting infrastructure in place, secure rights to pure water in Igiugig, and rights to fish for salmon in Nikolai. In addition, there were some problems such as the high cost of energy that were faced by all communities. Each community found *different* ways to address this problem.
2. *Create an environment of mutual respect for multiple ways of knowing*. Scientists should be encouraged to engage respectfully in indigenous venues such as talking circles at regional tribal meetings (ANSC 2003–04; Huntington 2007), knowledge-

sharing networks (ANKN 2012), and tribal newsletters (Huntington and Huntington 2005). In response to a letter from Caleb Pungowiyi to the Marine Mammal Commission in 1998 pointing out that few scientists were taking seriously the observations of Native hunters and elders about climate change, a workshop was organized on changes in arctic sea ice and environment that had equal participation and engagement by scientists and Native experts (Huntington 2000b). This workshop led to a 1-year pilot project on *Watching Ice and Weather Our Way* that was conceptualized, designed, and implemented by Yupik experts (Krupnik 2002). There are still substantial barriers to communicating ideas between knowledge systems with respect to both the language that is used and the confidence in the ideas that are shared (Cajete 2000; Kovach 2009). Peer review is important in both oral traditions and western science, but the process is quite different. Over the longer term, educational reforms are necessary that acknowledge both knowledge systems and recognize the value of hands-on outdoor learning in an indigenous context, as in culture camps and involvement of youth in subsistence harvest.

3. *Directly assist communities in achieving their adaptation goals*. The Newtok Planning Group is a collaboration of 25 government agencies, tribal groups, and non-governmental organizations, led by the Newtok Traditional Council, that assists Newtok in designing and implementing a plan to relocate from its current site which is vulnerable to climate change-induced flooding and erosion to a site selected by the community (Bronen 2011). Other efforts seek to address climate change at larger scales. For example, the Inuit Circumpolar Council (ICC) claimed in 2005 in their Petition to the Inter-American Commission on Human Rights that rapid high-latitude warming and its unprecedented impacts on ecosystems and indigenous communities violate their human rights (http://www.inuitcircumpolar.com/, Trainor et al. 2007). In their petition, the ICC asked that the United States be required to reduce its carbon emissions in order to protect the human rights of northern indigenous peoples.
4. *Promote partnerships that foster effective climate solutions from both western and indigenous perspectives*. This requires moving beyond simply collecting or citing traditional knowledge to applying traditional knowledge in problem-solving. Working in true partnership involves recognizing, respecting, and, where appropriate, resolving epistemological differences in devising place-based solutions (Trainor in press; Voggesser et al. 2013; Whyte 2013). Scientists across the Arctic are increasingly working with indigenous communities to co-design the science (Krupnik and Jolly 2002), as in the Bering Ecosystem Study (http://www.arcus.org/bering/projects.html) and the U.S.-Canada Arctic Borderlands Project (Kofinas et al. 2002). Sometimes, however, co-management efforts fall short of addressing the needs for both cultural and ecological integrity (Robards and Lovecraft 2010). When successful, such collaborative efforts can also lead to the identification of local and tribal measures in response to the challenges that have been jointly identified (e.g., Salomon et al. 2011).
5. *Foster regional and international networking to share climate solutions*. As indigenous communities strive for sustainable adaptation in response to climate impacts, communities can learn from each other how to document observations, devise and implement adaptation solutions, and overcome barriers in funding, information exchange, and institutional hurdles. In many cases, the most appropriate venues will be conferences of indigenous peoples, such as the Indigenous Peoples' Global Summit on Climate Change held in Anchorage in 2009 (www.un.org/ga/president/63/letters/globalsummitoncc.pdf) or websites maintained by tribal organizations (e.g., the Alaska Native Science Commission, Inuit Circumpolar Council). There is scope for substantial innovation to link more

effectively the communication networks of tribes, scientists, and managers who share a common goal in fostering effective adaptations to climate change. The Exchange for Local Observations and Knowledge in the Arctic (ELOKA; www.eloka-arctic.org) fosters the "collection, preservation, exchange, and use of local observations and knowledge of the Arctic," partnering with indigenous communities, researchers, and others who share this goal to devise new approaches to building networks and establishing connections between people with common interests and goals (Pulsifer et al. 2012).

Much work has been done to date on each of the five prongs, but more is needed, especially in the transition from strong individual projects to larger efforts to connect and draw from individual successes. Greater recognition of the larger body of practice and improved ability to draw upon the lessons of others will remove the sense of isolation that can constrain resilience and foster collaborative problem-solving. This in turn will help Alaska Native communities better characterize the challenges they face and better design solutions that will work in their communities on their terms.

Acknowledgments We thank Julie Maldonado and the U.S. National Climate Assessment for organizing this special issue and the Alaska Native Science Commission for its leadership in indigenous science in Alaska since 1993.

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DOI 10.1007/978-3-319-05266-3_6
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0852-y

Climate change impacts on the water resources of American Indians and Alaska Natives in the U.S.

K. Cozzetto · K. Chief · K. Dittmer · M. Brubaker · R. Gough · K. Souza · F. Ettawageshik · S. Wotkyns · S. Opitz-Stapleton · S. Duren · P. Chavan

Received: 26 November 2012 / Accepted: 16 July 2013 / Published online: 30 August 2013

Abstract This paper provides an overview of climate change impacts on tribal water resources and the subsequent cascading effects on the livelihoods and cultures of American Indians and Alaska Natives living on tribal lands in the U.S. A hazards and vulnerability framework for understanding these impacts is first presented followed by context on the framework components, including climate, hydrologic, and ecosystem changes (i.e. hazards)

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-013-0852-y) contains supplementary material, which is available to authorized users.

K. Cozzetto (✉)
Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA
e-mail: kcozzetto@colorado.edu

K. Chief
Department of Soil, Water, and Environmental Sciences, University of Arizona, Tucson, AZ, USA

K. Dittmer
Columbia River Inter-Tribal Fish Commission, Portland, OR, USA

M. Brubaker
Alaska Native Tribal Health Consortium, Anchorage, AK, USA

R. Gough
Intertribal Council on Utility Policy, Rosebud, SD, USA

K. Souza
PRiMO, Indigenous Ecological Knowledge Circle, Honolulu, HI, USA

F. Ettawageshik
United Tribes of Michigan, Harbor Springs, MI, USA

S. Wotkyns
Institute for Tribal Environmental Professionals, Flagstaff, AZ, USA

S. Opitz-Stapleton
Staplets Consulting, Boulder, CO, USA

and tribe-specific vulnerability factors (socioeconomic, political, infrastructural, environmental, spiritual and cultural), which when combined with hazards lead to impacts. Next regional summaries of impacts around the U.S. are discussed. Although each tribal community experiences unique sets of impacts because of their individual history, culture, and geographic setting, many of the observed impacts are common among different groups and can be categorized as impacts on—1) water supply and management (including water sources and infrastructure), 2) aquatic species important for culture and subsistence, 3) ranching and agriculture particularly from climate extremes (e.g., droughts, floods), 4) tribal sovereignty and rights associated with water resources, fishing, hunting, and gathering, and 5) soil quality (e.g., from coastal and riverine erosion prompting tribal relocation or from drought-related land degradation). The paper finishes by highlighting potentially relevant research questions based on the five impact categories.

1 Introduction

Water is sacred. This is tradition. In contrast to the non-tribal utilitarian view of water, Native Americans revere water and water is life. It is integral to many Native American practices such as purification and blessing rituals and is used to acknowledge all relations and to establish connection to Mother Earth and Father Sky. Water is a holistic and integrating component connecting continents, humans, animals, and plants through a continuous cycle of liquid, solid, and vapor states. Without water, life would not exist as we know it. Water is the one thing we all need, all of us, all of life. As Native Americans, we honor and respect the tradition of water and must protect it always.

American Indians and Alaska Natives in the U.S. (AIAN) originate from diverse indigenous groups, each with a unique and rich tradition, culture, language, and history. Today there are 566 federally recognized tribes (supplemental Table S7) across 33 states and at least 34 state recognized tribes (Fig. 1). According to the 2010 Census, 5.22 million people are AIAN either fully or in part. While 78 % of AIAN live on non-tribal lands (cities and towns), this paper focuses on the over 1.14 million AIAN (22 %) living in tribal areas (supplemental Table S3).

This paper provides an overview of climate change impacts on tribal water resources (rivers, lakes, wetlands, springs, groundwater, permafrost, snowpack, glaciers, estuaries, oceans, and sea ice) and the subsequent cascading effects on AIAN livelihoods and cultures. We examine impacts in six regions: Alaska, Pacific Northwest, Southwest, Great Plains, Midwest, and East. Although Hawaii and unincorporated island territories were beyond the scope of this article, the impacts discussed for coastal areas are relevant for islands. First the paper presents a hazards and vulnerability framework to assist in understanding the severity and types of climate change impacts to tribal water resources. Then, context for the framework components is provided. Next, examples of regional impacts are summarized, and five categories of common impacts are identified. Finally, potentially relevant research questions based on the five impact categories are described. For more in depth discussion and additional examples for the various sections, we strongly encourage readers to make use of the extensive supplementary materials.

S. Duren
Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, USA

P. Chavan
Alaska Native Tribal Health Consortium, Anchorage, AK, USA

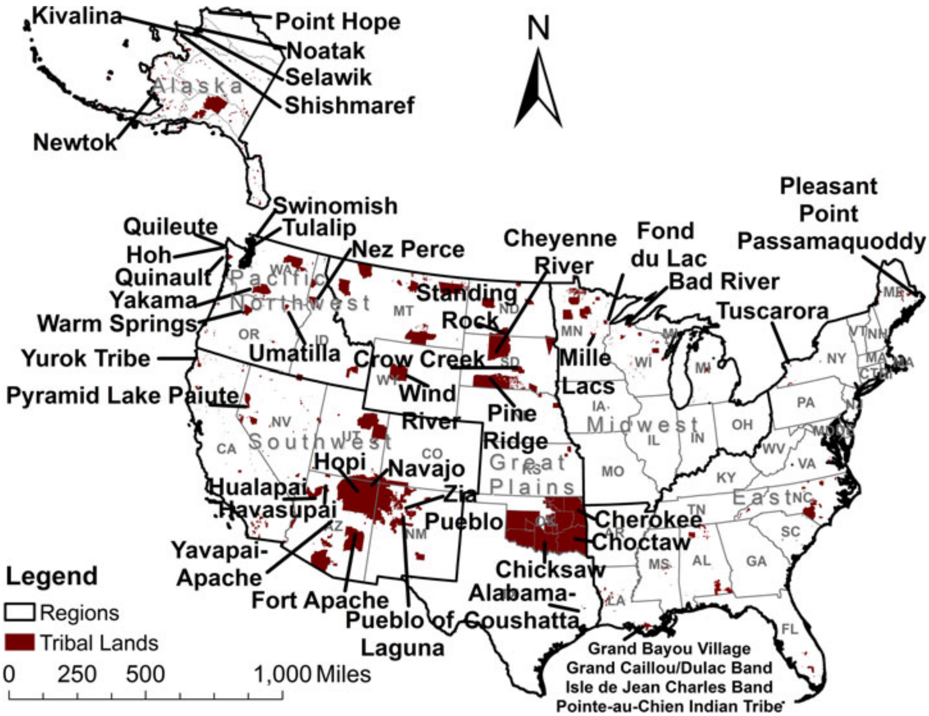

Fig. 1 Map showing the six regions and the locations of AIAN lands discussed. All *shaded areas* represent tribal lands. Source: U.S. Census Bureau

2 Framework for understanding impacts

The vulnerability of AIAN to climate change can be examined through a variety of frameworks. In this paper, we draw from hazards and disaster risk reduction research and describe vulnerability as the interconnectedness of factors constraining or enabling the ability of people to respond to hazards and exposing them to climate change and variability hazards (Fig. 2). Constraining or enabling factors contributing to vulnerability and/or adaptive capacity include socioeconomic, political, infrastructural, and environmental factors and spiritual and cultural values (Cutter et al. 2010; Füssel and Klein 2006). Whether or not an impact proves to be beneficial or detrimental depends on tribal vulnerability or adaptive capacity and the nature (severity and frequency) of the climate hazard. To summarize, vulnerability and adaptive capacity are functions of human and environmental factors and exposure to climate hazards. Impacts are functions of vulnerability and the nature of climate hazards.

3 Hazards and vulnerability context

Similar to other indigenous people around the world, AIAN residing on tribal lands in the U.S. often live in small, rural communities, under lower socioeconomic conditions, and are frequently politically marginalized (Nakashima et al. 2012; UN 2009). AIAN depend more on subsistence livelihoods and have deep spiritual and cultural connections with their waters and lands. This section describes the types of climate, hydrologic, and ecosystem changes

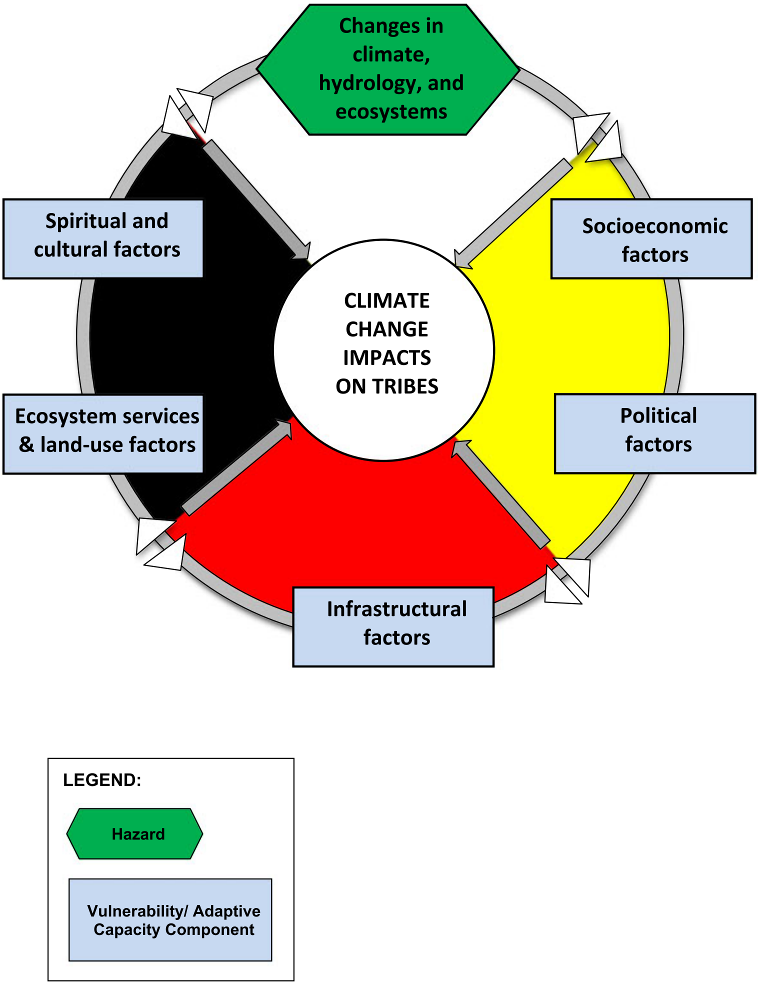

Fig. 2 Conceptual framework showing how climate change impacts are the outcome of vulnerability/adaptive capacity contexts and the nature (severity and frequency) of climate hazards

that constitute hazards experienced by tribes. It also describes sets of vulnerability/adaptive capacity factors that are common for many tribes, although, again, each tribe's situation is unique. Although we separate vulnerability factors into various categories for ease of conceptualization, these factors, as indicated in Fig. 2, will affect one another.

3.1 Climate, hydrologic, and ecosystem change hazards

Climate variability and change are currently resulting in or are likely to result in increased temperatures, changes to precipitation regimes, and increases in extreme events (CCSP 2008). These climatic changes are altering regional hydrology (i.e., quantity, quality, timing) in many ways such as permafrost thawing and earlier snowmelt (additional examples in supplemental Table S1). Changes in climatic and hydrologic parameters will lead to ecosystem changes. These can include habitat loss and altered nutrient cycling (Tillman and Siemann 2011). They also include changes related directly to species, for instance, shifts in their geographic ranges and changes in population numbers (additional examples in supplemental Table S2). These types of changes constitute hazards to which AIAN are exposed. Ecosystem changes affect ecosystem services, as discussed below.

3.2 Socioeconomic factors

Factors such as community structure and rural–urban composition are recognized components of social vulnerability (Cutter et al. 2010). An examination of 2010 Census data for over 400 tribal lands (supplemental Table S3) shows that 69 % of AIAN communities have fewer than 2,000 people (AIAN and non-AIAN populations combined). Within these communities, 78 % of residents live in rural and 22 % in urban areas. These small, rural AIAN communities often have higher water supply costs because of greater transportation costs and smaller economies of scale (USEPA 2001). These higher costs are combined with economic conditions that are generally much lower than the U.S. average. The Census Bureau's 2006–2010 American Community Survey provides economic data for AIAN living in approximately 300 tribal areas. The average unemployment percentage (15 %) is nearly double the U.S. average (supplemental Table S3). The median household income is $33,379 or 36 % below the national average, and more than a quarter (29 %) of people live below the poverty level. A 2005 Bureau of Indian Affairs (BIA) report that uses different methods than the Census Bureau estimates higher unemployment (49 %) for AIAN living on or near tribal lands (supplemental Sec. 3.2). These economic conditions affect the management of tribal water resources (Sec. 3.4).

3.3 Political factors

Federally recognized tribes are domestic dependent nations with inherent rights of self-governance. Treaties, court decisions, and tribal legislation define this sovereignty and govern relationships between the tribes and outside entities (Houser et al. 2001). When tribes entered into treaties defining reservation lands, geographic boundaries became fixed for the first time in Native history. This restricted traditional migration practices, which were critical strategies for adapting to changing water resources and species movement (Gautam et al. 2013). Often, tribes were settled on remnants of their original land base or forcibly relocated to lands that were less valuable in terms of water resources and agricultural potential (Houser et al. 2001). Some tribes specifically reserved the rights to fish, hunt, and gather in customary areas off-reservation in treaties. However, these place-based rights may become geographically mismatched with species distributions as ranges shift in response to climate changes (Houser et al. 2001).

The foundational legal decision protecting tribal water resources is the 1908 *Winters* case [207 US 564 (1908)], which recognized that when tribes reserved reservation lands they also reserved the water rights necessary to fulfill the purpose of the reservation. Many of these "federal reserved rights" have yet to be adjudicated or exercised in full and many tribes are still in the process of negotiating with other stakeholders to quantify tribal water rights. Tribes who litigated and won water rights often did not receive infrastructure funding and subsequently are struggling to finance infrastructure to develop their water rights.

Off-reservation water use and pollution have direct impacts on tribal water resources yet tribes are often underrepresented in water resource management discussions and decision-making processes. Similarly, some international water commitments have not considered tribal rights (Houser et al. 2001). Climate change impacts on water quantity, quality, and timing add to legal and planning complexities and compound concern that Indian water rights may be sacrificed under climate change resulting in unmet present and future human and environmental water demands.

3.4 Infrastructural factors

Water infrastructure pertains to physical structures (e.g., water supply and wastewater treatment plants, stormwater drainage systems, etc.) used to manage water for a variety of purposes (e.g., drinking, industrial, hydropower, agriculture, ranching). Changing climate, hydrologic, and ecologic regimes are creating conditions that tribal infrastructure may not be designed to accommodate, resulting, in cases, in the deterioration of physical structures and decreasing effectiveness (e.g., ability to treat water to a specified standard). This can lead to service disruptions with resulting economic and public health consequences.

Generally poorer economic conditions on tribal lands may mean that infrastructure is lacking, inadequate, or poorly maintained, increasing tribal vulnerability to flooding, drought, and waterborne diseases. Climate-related infrastructure damage can increase costs of providing water, which can quickly drain tribal financial reserves as funds are expended for emergency response (supplemental Sec. 3.4). Approximately 12 % of AIAN homes lack safe and adequate water supplies, and/or waste disposal facilities as compared to less than 1 % of the U.S. (IHS 2013). In some tribal areas, particularly in Alaska and the Navajo Nation, considerable portions of the population, 13 % and 25–40 % of households respectively, haul water (ITFAS 2008; NDWR 2003). Even without climate-related impacts, water haulers are more susceptible to waterborne diseases, especially if water is obtained from nonpotable sources (e.g., livestock wells) or if unsanitary hauling methods are used (ITFAS 2008).

3.5 Ecosystem services and land-use factors

People benefit from ecosystems in a variety of ways. These benefits are sometimes described as ecosystem services of which there are four commonly used categories: 1) provisioning (e.g., supply of food and water), 2) regulating (e.g., purification of wastewater discharged into a stream), 3) cultural services (e.g., supplying spiritual or recreational opportunities), and 4) supporting (e.g., photosynthesis, which supports food provisioning) (MEA 2005). Because climate changes can lead to ecosystem changes, climate changes affect ecosystem services. In addition, tribal ecosystem health and services are degrading because of depressed economic conditions, attempts to maintain traditional livelihoods on fixed, marginal lands (Sec. 3.3), urbanization, land-use changes, and invasive species (supplemental Box S6). One important ecosystem service for AIAN is provided by groundwater, which supplies 93 % of American Indian and 66 % of rural Alaska Native drinking water systems (USEPA 2001; ANTHC 2011). Others are provisioning of subsistence or supplemental foods and of spiritual and cultural services (see Sec. 3.6).

3.6 Spiritual and cultural factors

AIAN are intimately connected to the places in which they live through spiritual and cultural livelihoods and values. They are keepers of complex and extensive bodies of ecological and societal knowledge passed on through generations (UN 2009). They strongly associate cultural identities and traditional knowledge with their waters and lands and seek spiritual and religious inspiration from them. Particular locations such as mountains or springs are held sacred and certain waters may be used for ceremonial purposes. In addition, many tribes respect and hold sacred the individual role of species on Mother Earth and thus impacts on these species are of inherent concern to tribes. Traditional ecological knowledges (Wildcat this issue) contribute to human cultural diversity and are a repository of long-term observations of environmental changes that have occurred and of adaptation strategies that have been effective in the past. This knowledge may be able to extend the environmental record in data sparse regions, improve monitoring design, and contribute to the future adaptive capacity of AIAN (supplemental Boxes S8 and S9).

4 Impacts

Climate change impacts to tribal water resources, livelihoods, and cultures are as diverse and unique as individual tribes and their cultures and geographic settings. However, based on our review, we have identified five categories of common impacts. These include impacts on: 1) water supply and management (including water sources and infrastructure), 2) aquatic species important for culture and subsistence, 3) ranching and agriculture particularly from climate extremes (e.g., droughts, floods), 4) tribal sovereignty and rights associated with water resources, fishing, hunting, and gathering, and 5) soil quality (e.g., from coastal and riverine erosion prompting tribal relocation or from drought-related land degradation). Several accompanying papers in this special issue expand on these themes, including the impacts of climate change on traditional foods (Lynn et al. 2013), a broader range of impacts for Alaska Natives (Cochran et al. 2013), and the relocation of tribal communities (Maldonado et al. 2013). As discussed below, observed impacts are predominantly detrimental. In addition to impacts, we have, in cases, also noted contributing vulnerability factors. For more information on impacts described and additional examples and references, we refer readers to the supplemental materials.

4.1 Alaska

Alaska, which is as large as one third of the continental U.S., is home to 227 federally recognized Alaska Native villages and communities (supplemental Table S7). Most of the villages are small and isolated, and many residents engage in traditional subsistence hunting (e.g., walruses, caribou), fishing (e.g., salmon), and gathering and are highly dependent on the state's rich water resources (ADFG 2010). Much of the water is frozen most of the year or locked up in glaciers or frozen ground. However, the Arctic including Arctic Alaska is experiencing some of the most profound warming in the world (IPCC 2007). In this section, we focus on impacts on Arctic Alaska Natives, most of whom live along the coast, and on water supply related impacts for the entire state. Key Arctic impacts include those on subsistence activities and coastal and riverine erosion. Key water supply impacts include those on source waters and related infrastructure.

Life for many Arctic Alaska Natives revolves around the hunting of sea mammals such as seals and whales, and sea ice plays an important role. Thinner ice and unusual cracks can create hazardous conditions leading to injuries and equipment loss (Mahoney et al. 2009). Timing shifts in sea ice freezing and thawing due to warming is altering hunting patterns. Permafrost thawing is making underground cellars used for storing food much less reliable (Brubaker et al. 2010). Storm surges exacerbated by delays in autumn sea ice development contribute to coastal erosion that is occurring to such a degree that some Native villages, such as Kivalina, are being forced to consider relocation at costs estimated in the hundreds of millions of dollars (Gray 2007). Permafrost thawing is contributing to riverine erosion with similar relocation concerns (Bowden et al. 2008).

Rural Alaska Native communities both in the Arctic and elsewhere in Alaska depend on groundwater (66 %), lakes and reservoirs (20 %), and rivers and creeks (14 %) for their water supply (ANTHC 2011). Little information is available on changes to Alaska Native groundwater supplies, however, surface water sources and water supply infrastructure are being dramatically affected by climate changes (White et al. 2007). Algal blooms are increasing in lakes and rivers due to warmer temperatures, and in villages, like Point Hope, they are causing significant increases in treatment time and costs (Brubaker et al. 2010). Beavers, which can carry giardia, are occupying rivers in northern Alaska for the first time since the last ice age and are an example of shifting wildlife acting as vectors for waterborne diseases (Brubaker et al. 2012). As permafrost thaws in various areas of Alaska, the ground can absorb more water, and some lake water levels are decreasing or lakes are draining entirely, causing water supply problems (Rover et al. 2012). Erosion driven by permafrost thawing can cause high river turbidity levels, resulting in boil water notices and increased risk of waterborne disease (Brubaker et al. 2012). Extreme precipitation events can lead to flood-related contamination and high turbidity levels that can overwhelm water treatment systems (Brubaker et al. 2012). Subsidence due to permafrost thawing and erosion are causing widespread physical damage to water infrastructure, sometimes interrupting services for months (supplemental Sec. 4.1).

4.2 Pacific Northwest

The Pacific Northwest (PNW) is home to 42 federally recognized tribes (supplemental Table S7). The Cascade Mountains run north–south through the region, dividing it into a coastal zone west of the Cascades and a continental zone east of the mountains. The region has an October–March precipitation season. Much of the precipitation is stored in mountain snowpack and released during the April–July snowmelt period. PNW rivers host several salmon species, which are cultural keystones and important food and economic sources for many PNW tribes. Salmon are coldwater fish that start life in fresh, headwater streams as eggs. The juveniles are flushed to lower river estuaries to acclimate to saltwater, then migrate to the ocean for two to five years before returning upriver as adults to spawn and die (Crozier et al. 2008). Water supplies are important for tribal salmon hatcheries and reintroduction efforts (CRITFC 2013), riparian restoration, forestry, agriculture, small-scale hydropower, and municipal uses. Key climate change impacts include effects on salmon and shellfish, coastal erosion, and the exercise of treaty rights.

Storm intensities during the early part of the wet season are increasing (CIG 2012) and can lead to increased flooding, habitat scouring, and washing away of buried salmon eggs. Warming air temperatures can shift snowmelt to earlier in the spring, which may lead to lower summer flows and unfavorably warm water temperatures (Dittmer 2013). Salmon may respond by migrating downstream earlier; however, this change may be mismatched with downstream conditions (Crozier et al. 2008). Warmer summer water temperatures are already affecting the migration of returning adult salmon. In summer 2003, for instance, salmon paused their upstream migration, remaining below the Bonneville Dam on the Columbia River for four weeks until temperatures cooled.

West of the Cascades, changes in coastal processes are also affecting tribes. In addition to salmon, the Swinomish (WA) rely on various shellfish as staples of food and culture. The tribe identified inundation from sea level rise and flooding from storm surges as major climate change threats to its estuaries, which provide critical habitat for shellfish and juvenile salmon (SITC 2010). Ocean acidification can disrupt the calcification process involved in shell development and affect the reproduction and growth of marine organisms (Ingram et al. 2012). Traditional foods like roots and berries are suffering from increased soil salinization due to sea-level rise (Papiez 2009). For the Quileute Nation and Hoh Tribe (WA), increased winter storms are coinciding with high tides at the Quileute and Hoh river mouths to create high storm surges that are washing away tribal lands. The Quileute are considering relocation. The Hoh are relocating to National Park Service land (ITEP 2012). Species migration out of traditional areas seems to be increasing (Papiez 2009). Treaty-protected rights to hunt, fish, and gather are typically linked to reservation locations or customary areas on public lands. Tribes like the Tulalip (WA) are concerned that, as species move, their distributions may become mismatched with locations of access.

4.3 Southwest

In the Southwestern U.S. (SW) from California to Utah and Arizona live 170 federally recognized tribes (supplemental Table S7) with small and large land holdings set in ranching, agriculture, mining, tourism, and other economies. Key climate change impacts stem from drought and flooding that affect livestock, agriculture, water supply, water rights, soil quality, and aquatic species.

Increasing aridity and drought threaten SW tribal cultures, pushing them to use marginal resources. Most of the 21 Colorado Plateau tribes have experienced drought for more than a decade (Redsteer et al. 2012). In the SW, drought is expected to increase in frequency and severity in the future (supplemental Table S1). On Navajo and Hopi lands in Arizona, lack of moisture has extended sand dune growth and migration to a third of the reservations, covering housing, causing transportation problems, and contributing to loss of endangered native plants and grazing land (Redsteer et al. 2011, 2012). On the Navajo Reservation, 25–40 % of residents haul water for household use at costs 20 times more than for non-Navajo water users in surrounding areas while per capita income is less than half the U.S. average (NDWR 2003). According to one study, the average trip was 14 miles one way (ITFAS 2008). During drought, increased traveling distances to water bearing public systems and doubled water-hauling costs are common challenges (NDWR 2003).

In Arizona, the Hualapai Tribe depends on tourism, big-game hunting, cattle grazing, and forestry for revenue, and its economy was greatly impacted by a multiyear drought in the early 2000s (Knutson et al. 2006). The drought forced the tribe to sell approximately 500 of its cattle because of supplemental water and feed costs. Other impacts included more wildfires, road closures due to wildfire threat, increases in invasive species and wildlife disease, loss of wetlands, wind erosion and visibility problems, and increased operating expenses for a river rafting company (Knutson et al. 2006).

In Nevada, the Pyramid Lake Paiute Tribe is deeply connected to the unique ecosystem of Pyramid Lake, which is home to a native, endangered species called cui-ui, the tribe's primary cultural resource. Traditionally, Paiute people traveled to the lake for cui-ui spawning to gather and dry fish. Today, the tribal economy is centered on fishing and recreational activities at the lake. The lake's wetlands also provide reeds for basketry, which remains a symbol of native identity. In the future, drought, increased temperatures and reduced inflows will likely increase the lake's salinity leading to reduced biodiversity with dominance of warmer temperature and salt tolerant species (Gautam et al. 2013).

Extreme precipitation events have also affected SW tribes. The Havasupai Tribe in Arizona, for example, experienced several severe floods from 2008 to 2010 that damaged trails, campgrounds, and recreational areas in Havasu Canyon, greatly impacting tourism revenue (Wotkyns 2010). Over 20 southwestern tribes have reservation lands and associated water rights in the Colorado River watershed. Anticipated decreased flows due to climate change combined with rapid population growth are increasing the urgency of adjudicating and defining these rights (Cordalis and Suagee 2008).

4.4 Great Plains

The Great Plains extend from Montana to Texas with the Rocky Mountains marking the region's western edge. Historically, the Plains were predominantly grasslands and the range of vast bison herds. Today, 70 federally recognized tribes call the Great Plains their home (supplemental Table S7) and engage in subsistence and economic activities such as agriculture, ranching, tourism, energy extraction, and renewable energy production. Key climate change impacts include those on water supply, ranching, agriculture, and water for ceremonial uses stemming from climate extremes such as drought and flooding and from increased glacial melting and shifts in snowmelt timing.

In North Dakota, the Standing Rock Sioux Tribe depends on a sole intake pipe from the Missouri River at Fort Yates for its water supply. A 2003 drought caused water levels to drop so low that silt and sludge clogged the pipe. The tribe did not have water for several days and an Indian Health Service hospital had to temporarily shut down (Albrecht 2003). In 2011, Oklahoma and Texas experienced a historic drought and heat wave. Drought impacts noted by the tribes included difficulties producing enough food for sustenance and hay to feed cattle (Riley et al. 2012). The lack of hay combined with the drying of stock ponds forced farmers to sell their livestock prematurely and depressed markets resulted from the accelerated selloff. Low water levels contributed to fish die-offs and blooms of blue-green algae. Tribes relying on hydropower had difficulty meeting energy needs and drying soils shrinking and compacting around pipes caused water main breaks. Flowing water, crucial for many tribal ceremonies, was lacking. Drought can amplify wildfire and flooding risks by creating dry conditions that provide increased fuel for high intensity fires, which in turn create water repellent post-fire soils that lead to increased runoff and subsequent debris flows that decrease water storage capacity (NWF 2011; Moench and Fusaro 2012).

Flooding can cause various impacts as well. In February 2011, the Pine Ridge Reservation (SD) experienced unusually early flooding when statewide high temperatures reached 40–70 °F, causing premature snowmelt (Skadsen and Todey 2011). This, combined with ice jams and clogged culverts, resulted in flooding throughout much of the reservation, and emergency drinking water and supplies had to be delivered to stranded residents (ICTMN 2011). Tribes often have widely dispersed populations that can make emergency response to situations like this challenging.

Residents of the Wind River Reservation (WY) depend on Rocky Mountain snowmelt for irrigation water, and during times of earlier snowmelt concerns about water for late season agricultural irrigation arise. In addition, flooding from the dramatic glacial retreat in the Wind River Mountain range is causing silt build up in irrigation ditches (NWF 2011). In some Rocky Mountain areas, dust from anthropogenically-disturbed soils may contribute to earlier snowmelt (Painter et al. 2010) and exacerbate impacts from warming temperatures.

4.5 Midwest

The Midwest (MW) is the location of the five lakes comprising the Great Lakes that together form Earth's largest surface freshwater system. Thirty federally recognized tribes live in MW states and depend on this resource (supplemental Table S7). Ceremonies honoring the waters as the life-blood of Mother Earth are held throughout the region. MW tribes depend on the waters for subsistence and commercial fishing and for water-based plant materials for traditional crafts and artwork (Tribal and First Nations Great Lakes Water Accord 2004). Additionally, most MW tribes now operate gaming facilities and other tourism enterprises that rely heavily upon water for aesthetic and recreational uses (Tribal Gaming in the States 2007).

Many MW tribes consider climate change adaptation to be one of the most important long-range environmental issues for tribal nations. Michigan tribes, for instance, have worked with the state to negotiate and sign the May 12, 2004 Intergovernmental Accord between the Federally Recognized Indian Tribes in Michigan and the Governor of the State of Michigan Concerning Protection of Shared Water Resources and the June 11, 2009 Intergovernmental Accord between the Tribal Leaders of the Federally Recognized Indian Tribes in Michigan and the Governor of Michigan to Address the Crucial Issue of Climate Change. Biannual meetings are held between the state and tribes to discuss shared responsibilities and potential cooperative efforts.

Impacts on MW tribes are diverse. Key impacts are related to flora and fauna important for diet, acknowledging clan responsibilities, social and mental health, and the exercise of treaty rights. Traditional healers in the region, for instance, have noted that lack of moisture and unreliable springtime temperatures have caused significant wild and cultivated crop losses (traditional healers, personal communication; CIAB 2012).

Wild rice (manoomin) is a sacred food of great importance to the Ojibwe of the Great Lakes area and may be detrimentally affected by climate change. In the Ojibwe Migration Story, The Great Mystery foretold the coming of the light-skinned race and instructed the Ojibwe to journey westward until they found “the food that grows on water.” Since the 1900s, the loss of wild rice acreage to mining, dams, and other activities has been substantial (FDLNR 2013). Warmer temperatures could cause further losses by reducing seed dormancy, favoring invasive, outcompeting plants, and being conducive to brown spot disease (MDNR 2008). Water levels also influence rice survival. Extremely low Lake Superior levels in 2007 forced the Bad River Band of the Lake Superior Tribe of Chippewa (WI) to cancel its annual wild rice harvest due to dramatic crop reductions (UW Sea Grant 2007). A 2012 flood led to near total wild rice crop failure on the Fond du Lac Reservation (T. Howes 2013, personal communication).

Tribes in the Great Lakes area rely on treaty fishing, hunting, and gathering rights. The exercise of these rights requires considerable attention to environmental issues, including climate changes that affect species and habitats. These rights have been the subject of several court cases, which have resulted in decisions upholding tribal rights.

4.6 East

The eastern U.S. extends from Maine to Florida and Louisiana. Twenty-seven federally recognized tribes live in the region (supplemental Table S7). Tribal members rely on natural resources to provide them with food and spiritual sustenance. Many tribal members engage in fishing (e.g., lobsters, shrimp), hunting (e.g., moose), and gathering (e.g., blueberries, medicinal plants) and rely on diverse water resources including riverine, estuarine, and oceanic ones. Key climate change impacts include those on aquatic species of cultural and livelihood importance and coastal erosion.

Riverine tribal communities may be exposed to higher incidences of flooding as a result of increased snowfall and rapid snowmelt (Horton et al. submitted). Fishery habitat may also be affected by flooding, as high river flows can potentially scour fish habitat and nesting sites, increasing fish mortality.

Coastal tribes obtain sustenance and employment from shellfish harvesting and fishing. Similar to the PNW, ocean acidification may affect the ability of shellfish to process calcium and magnesium carbonate and impact shell development (Ingram et al. 2012). Tribes in coastal Louisiana have identified land loss, which is leading to concerns about relocation, and saltwater intrusion, which is affecting the ability of tribal members to farm, as major issues (Louisiana Workshop 2012). These changes stem from a complex combination of human and environmental causes to which climate change may be contributing. Factors in one or both issues include canal construction associated with oil extraction; subsidence; levee systems leading to decreased sediment deposition; storms; and erosion (Bethel et al. 2011). Rising sea levels can also contribute to inundation leading to land loss and saltwater intrusion (Nicholls and Cazenave 2010). The Gulf of Mexico along the Louisiana/Texas coast is the location of one of the world's largest zones of coastal hypoxia, which is a concern for tribes. Climate changes could exacerbate/lessen hypoxia by, for example, increasing/decreasing river discharges and associated nutrient delivery into coastal areas, however, other factors like rising populations will likely lead to increased nutrient loads (Rabalais et al. 2009; supplemental Sec. 4.6).

The fishing/shellfish livelihoods of both riverine and coastal tribes may be affected by warming water temperatures, which can result in lower oxygen levels and greater susceptibility to parasites and disease that can stunt growth and increase juvenile mortality (Frumhoff et al.

Table 1 Examples of potentially significant research questions based on the five impacts categories

1) Impacts on water supply and management (including water sources and infrastructure)
  - How will climate change and other vulnerability factors such as population growth and land use changes affect the quantity and quality of AIAN surface and groundwater?
  - Given the importance of groundwater for AIAN drinking water systems, how can groundwater-surface water systems be collaboratively and conjunctively managed to maintain the viability and quality of AIAN aquifers?
  - What are the most effective ways (in terms of decreasing health risks, time, costs) for addressing water supply deficiencies in Indian Country, while taking climate change into account?
  - How can AIAN water supply infrastructure be better adapted to the climate changes occurring (e.g. drought, permafrost melting, algal blooms)?

2) Impacts on aquatic species important for culture and subsistence
  - Which species are particularly important to tribes for culture and subsistence (acknowledging that for many tribes all species are inherently important)?
  - How are and will climate changes and other vulnerability factors (e.g., habitat fragmentation) affect the geographic ranges and populations of such species?
  - What partnerships are needed and what strategies can help promote species resilience and transition?

3) Impacts on ranching and agriculture particularly from climate extremes (e.g., droughts, floods)
  - How can AIAN ranching and agriculture be made more resilient to climate extremes such as drought and flooding?

4) Impacts on tribal sovereignty and rights associated with water resources, fishing, hunting, and gathering
  - What are the potential impacts of climate change on tribal water rights (both in terms of quantity and quality) and off-reservation rights to fish, hunt, and gather?
  - How can climate change considerations be incorporated into AIAN water rights negotiations?
  - What types of legal and governmental processes can be put into place to allow tribes to renegotiate off-reservation rights to fish, hunt, and gather if species migrate to new areas?

5) Impacts on soil quality (e.g. coastal and riverine erosion prompting tribal relocation and drought-related land degradation)
  - Which tribes have a higher risk of losing their lands due to climate-related changes (e.g., coastal inundation, melting permafrost, coastal and riverine erosion) and to other vulnerability factors (e.g., levee systems leading to decreased sediment deposition and land buildup, unsustainable resource extraction) or have a higher risk of lands becoming unusable due to factors such as drought-related soil degradation and sand dune formation and migration?
  - What strategies can be put into place to decrease land loss or restore degraded lands?
  - What types of governmental processes (tribal and federal) can be put into place to assist tribes with identifying lands and funds for relocation if that becomes a necessity?
  - How can sites and/or practices that may be lost be documented most effectively?

2007). Although warming in the Northeast's colder water, particularly in the eastern Gulf of Maine, could boost lobster productivity, warmer waters may also be more hospitable for a bacterial condition known as lobster shell disease that grotesquely scars lobster shells making them less lucrative for sale (Frumhoff et al. 2007) impacting northeastern coastal tribes like the Pleasant Point Passamaquoddy in Maine who harvest lobster. Tribal communities often consume higher amounts of fish and shellfish than the average population increasing their exposure to methylmercury accumulated in seafood. One study found that warming oceans may facilitate the methylation of mercury and its uptake by fish (Booth and Zeller 2005).

5 Concluding thoughts

From the discussion above, it is evident that tribes have an urgent need to prepare for and respond to climate change impacts and that tribes as well as non-tribal entities supporting such efforts need to do so in a way that considers cultural values. In addressing these issues, it is important to take into account not only climate hazards but also socioeconomic, political, and other factors (Fig. 2) that contribute both to a community's vulnerability and adaptive capacity. In the supplemental section, we have provided an extensive table (Table S6) with general categories of actions that could increase the adaptive capacity of tribes, how they relate to contributing hazard and vulnerability factors, and examples of such actions currently taking place.

More specifically, Native American tribes need relevant and culturally appropriate (supplemental Sec. 5) monitoring, assessment, and research on their waters and lands and to develop or be included in the development of contingency, management, and mitigation plans. Tribes also greatly need actual implementation of projects. Although climate change preparedness can take place as a stand-alone effort, climate change considerations can be included as part of planning and implementation that is already occurring (supplemental Table S4).

Tribes or intertribal organizations must decide what constitutes relevant work. In Table 1, we propose research questions that might be significant for tribes based on the five impact categories. These include examples of science, policy, and social science questions related both to further identifying impacts and contributing climate and vulnerability factors and to identifying adaptation strategies.

To the benefit of adaptation processes, traditional ecological knowledges (TEKs) (Wildcat this issue) should be incorporated at all stages in a way that respects individual and tribal sovereignty over these TEKs. Capacity building in the form of training, employment, and education opportunities will enhance tribes' abilities to conduct their own assessments and implementation. Many tribes have unquantified and/or undeveloped water rights, which makes planning for tribes and others in a region more challenging (Collins et al. 2010). It is thus imperative that tribes adjudicate and solidify their water rights and that water management polices be designed to consider climate change scenarios while also considering tribal rights. Many tribes have a great need for monitoring to help identify the environmental changes that are occurring and to assess the effectiveness of adaptation strategies (Collins et al. 2010). Because tribes are stretched thin in addressing current problems, much less preparing for future climate change impacts, funding strategies to assist with all stages of climate change preparedness are critical. In the aforementioned undertakings, tribes can take advantage of partnerships with government entities, nonprofit organizations, universities, tribal colleges, and one another (supplemental Table S5). For in the end, like raindrops forming an ocean, we are all family, in relationship, and deeply connected.

Acknowledgments The authors would like to thank the following people for their valuable assistance with the manuscript preparation: D. Heom, J. Deems, J. Nania, J. Maldonado, M. Stover, N. Crowe, R. Pandya, T. Howes, and two anonymous reviewers.

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DOI 10.1007/978-3-319-05266-3_7
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0737-0

Climate change in arid lands and Native American socioeconomic vulnerability: The case of the Pyramid Lake Paiute Tribe

Mahesh R. Gautam • Karletta Chief • William J. Smith Jr.

Received: 27 November 2012 / Accepted: 4 March 2013 / Published online: 9 April 2013

Abstract The case of the Pyramid Lake Paiute Tribe exemplifies tribal vulnerabilities as a result of climate change. Preliminary socio-economic data and analysis reveal that the tribe's vulnerability to climate change is related to cultural and economic dependence on Pyramid Lake, while external socio-economic vulnerability factors influence adaptive capacity and amplify potential impacts. Reduced water supplies as a consequence of climate change would result in a compounded reduction of inflows to Pyramid Lake, thus potentially impacting the spawning and sustenance of a cultural livelihood, the endangered cui-ui fish (*Chasmistes cujus*). Meanwhile, limited economic opportunities and dwindling federal support constrain tribal adaptive capacity. Factors that contribute to tribal adaptive capacity include: sustainability-based values, technical capacity for natural resource management, proactive initiatives for the control of invasive-species, strong external scientific networks, and remarkable tribal awareness of climate change.

1 Introduction

Studies in the last two decades provide ample evidence of hydroclimatic changes in the Western U.S. linked to short and long term climate variability (Cayan et al. 2001; Coats 2010). In addition, Global Climate Model projections show temperature will significantly increase over the next 100 years and could disproportionately impact semi-arid regions of

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

M. R. Gautam
Desert Research Institute, Las Vegas, NV, USA

K. Chief (✉)
University of Arizona, Tucson, AZ, USA
e-mail: kchief@email.arizona.edu

W. J. Smith Jr.
University of Nevada, Las Vegas, NV, USA

the western U.S. (Barnett et al. 2005). One hotspot, where climate change impacts are potentially significant, is in the Sierra Nevadas where water rights have been contested for nearly a century (Wilds 2010). Recent studies in the Sierra Nevadas have exposed vulnerabilities to climate change in terms of hydrologic response (Dettinger et al. 2004; Maurer 2007) and hydropower (Vicuña et al. 2008). These studies integrate key northern Californian cities, but other sub-areas are not well studied, with the exception of Grantz et al. (2007) who studied Truckee and Carson River Basins for water management. The river basin of interest for our study, the Truckee River Basin (TRB) (Fig. 1) is nested within a this broader area of general research interest (Regonda et al. 2005). One common aspect of these studies is their focus on biophysical impacts and an implicit assumption that social vulnerabilities have a limited role in defining climate change impacts.

In TRB, tensions regarding water rights are high, and climate change may upset a delicate balance for Native American tribes like the Pyramid Lake Paiute Tribe (PLPT) in meeting water demands for a growing population and in maintaining healthy ecosystems. PLPT, the largest tribe in Nevada, is dependent on Pyramid Lake, which is the terminus of the Truckee River. The Truckee River begins at Lake Tahoe, with headwaters in California's Sierra Nevada Mountain Range and flows through semi-arid Reno-Spark area, metropolitan area, before terminating at Pyramid Lake. Pyramid Lake is extremely important for biodiversity, socio-cultural, and economic reasons and is home to the federally listed endangered fish cui-ui (*Chasmistes cujus*) and the threatened fish Lahontan cutthroat trout (LCT; *Salmo clarkii henshawi*).

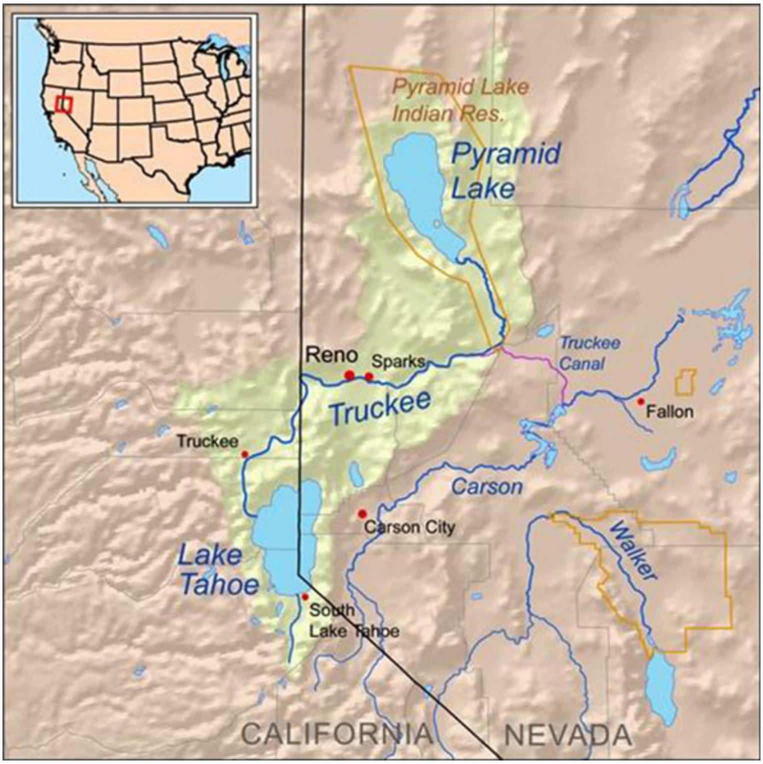

Fig. 1 Truckee River Basin Showing Pyramid Lake Indian Reservation (Credit to Karl Musser)

PLPT's legal rights and decision-making are important for two main reasons. First, they live at the river's terminal end which exposes them to upstream users and impacts. Second, their identity and livelihood are deeply connected, culturally and economically, to Pyramid Lake and its fish. PLPT's Paiute name is *Kuyuidokado*, or cui-ui eaters, named after the Pyramid Lake sucker fish which was one of their main food sources before its drastic decline in the early 1900's due to Derby Dam, water use, and drought. Culturally, the Paiute origin story is based on Pyramid Lake and its tufa-rock formation, called the Stone Mother that represents a woman with a basket whose tears created the lake (Wheeler 1987). Today, fishing and recreational activities are central to PLPT economy.

Like many Native American tribes, PLPT is especially vulnerable (Smith et al. 2001) to both climatic and non-climatic stressors because of their reliance on natural resources for spiritual and socio-cultural practices (Jostad et al. 1996); dependence on local natural resources (Adger 2003; Thomas and Twyman 2005); and lower socio-economic conditions (Sarche and Spicer 2008). However, literature on climate change impacts and climate change vulnerability of Native American tribes is lacking. One notable exception is the study of climate change impacts on the Inuit in Arctic Bay, Canada (Ford and Smit 2004). Despite similarity in socio-economic status and traditional values related to symbiotic relationships with nature, considerable variations of vulnerabilities exist across the diversity of Native American tribes and Artic indigenous communities (Cochran et al. 2013; Maldonado et al. 2013). This variation is shaped by factors internal to tribal society such as traditional and cultural preferences on livelihood means and practices, as well as external socio-economic and political factors.

Besides the traditional technical approaches, understanding PLPT's vulnerability to climate change requires thoughtful consideration of values, history, and other local socio-economic and political contexts. Byg and Salick (2009) underline the importance of local perception of climate change, impact assessment, and adaptation planning. Despite their importance, vulnerability assessments pose significant challenges due to contradictory definitions, multiple frameworks, and numerous discourses (O'Brien et al. 2007), nevertheless, there are increasing efforts to reconcile these approaches (Füssel 2007). In this study, we present an analysis of critical aspects of PLPT's social vulnerability to climate change that paves a way towards achieving an integrated analysis in the future that will merge biophysical and socioeconomic vulnerabilities and use model driven (top–down) and local perception-knowledge driven (bottom–up) approaches. The objectives of this study are to 1) identify and evaluate critical socio-economic factors contributing to the vulnerability of the Pyramid Lake Paiute Tribe to climate change impacts and 2) assess the adaptive capacity of the Pyramid Lake Paiute Tribe to climate change.

2 Methods

2.1 Surveys and interviews

Descriptive approaches were utilized in this study and qualitative data (PLPT perception and observation) were collected at household and organizational levels. Using a human ecology approach (Füssel 2007) that emphasizes human behavior and perception, a survey was conducted to assess value, belief, and perception on climate change impacts and vulnerabilities at the household level. In February 2010, questionnaires were mailed to 687 households with pre-stamped return envelopes. To increase the response rate from 5 % to 16 %, surveys were conducted house-to-house and at a powwow held on the PLPT reservation during November and December 2010. In January and May 2011, household surveys were followed by semi-structured interview with key executives of various PLPT departments (environmental managers and tribal council). A purposive and snowball sampling method (Kemper et al. 2003) was applied for both surveys where selected high level decision-makers, environmental managers, and recommended subjects were recruited for interviews. Following Ford and Smit (2004), broad themes and topics were prepared as an interview guide (Table 1). We supplemented these themes through secondary data collected from household surveys and published reports.

2.2 Vulnerability assessment framework

One of the critical problems in vulnerability assessment (VA) is defining vulnerability. As Adger et al. (2004) note IPCC framework has two different definitions – one describing outcome, and the other the context. Thus, these, two different definitions would lead two different outcomes (O'Brien et al. 2007; Adger et al. 2004). To tackle vulnerability, we utilized the IPCC's integrative framework for vulnerability (Eq. 1), where vulnerability as an outcome is a function of three variables: exposure, sensitivity, and adaptive capacity.

$$\text{Vulnerability} = f(\text{exposure, sensitivity, and adaptive capacity}) \tag{1}$$

Table 1 Interview checklist with key themes and topics covered (adapted from Ford et al. 2006)

Key theme	Topics covered
Context and Community Life	-Environmental Setting (geography, geology, climate, natural resources, etc.)
	-Family and Community Relationships (clans, kinship, family names, spiritual and government leaders, etc.)
	-Language, Culture, and Religion
	-Life Cycle (birth-death and major life markers, feasts, celebrations, and ceremonies)
	-Major Issues and Challenges (social and cultural with links to climate change)
	-Seasonal Activities (cultural, social, and livelihood)
	-Tribal Origin and History (migration patterns, creation stories, adaptation, colonization, western settlement, Indian wars, treaty and reservation era, boarding school era, civil rights, modern day, etc.)
Adaptive Capacity and Vulnerability	- Livelihood Assets or Capitals (financial, natural, physical, socio-cultural, and human)
	1. Climate Change Awareness
	2. Education
	3. Local Knowledge and Practices
	4.Income Diversification, Agricultural Dependence, and Seasonal Migration
	5. Social Capital (social network, inequality, individualism, social division and tension, income sharing within household, role of elders)
	-Institutional Arrangement and Capacity for EnvironmentalIssues
	-Institutional Support from External Agencies (e.g. federal government, NGO, environmental groups etc.)
	-Policies, Institutions and Processes (decision making, governance, resource use and access)
	-Power Relation and Access to Resources

Exposure refers to what is being exposed (the system that is at risk under climate change such as population, resources, or property) and the change in climate that the affected system will face (e.g. temperature, precipitation, extreme events, sea level etc.).

Adaptive capacity as defined in 4AR (IPCC 2007) is the ability of a system to successfully respond to climatic variation and change and is facilitated through adjustment in behavior, resources, and technology. Adaptive capacity is determined by socioeconomic and political factors: 1) Resources/assets; 2) Access to resource influenced by equity and sustainability; and 3) Support mechanisms (Eq. 2).

$$\text{Adaptive Capacity} = f[\text{resources/assets, access to resource (equity and sustainability), support mechanism}] \quad (2)$$

According to Füssel (2007), social vulnerability as well as biophysical vulnerability (outcome) can be better studied through considering both internal and external factors (Eqs. 3 and 4).

$$\text{Internal} = f(\text{Socioeconomic: social, cultural, attitudinal; Biophysical: local geography and environmental conditions}) \quad (3)$$

$$\text{External} = f(\text{Socioeconomic: national policy, power relation with regional stakeholders, external support; Biophysical: floods, droughts, temperature rise, reduced snowpack etc.}) \quad (4)$$

In this study following Adger et al. (2004), we retain the term biophysical vulnerability as risk (outcome) as in disaster risk reduction literature, which is a function of hazard, exposure, and sensitivity. While stressors and perturbations characterize hazard, social vulnerability and capacities explain the exposure, and sensitivity of the systems. Following Füssel (2007), we classify socioeconomic factors as the one internal to the system and dependent on factors such as local response capacity which operate at local scale (e.g. based on chosen scale of analysis it can be household or community or state) or external (external socio-economic, political, environmental factors) operating at larger scale (e.g. national policies, external assistance, economic globalization).

3 Context and community life

Indigenous people have inhabited the Great Basin (a multi-state endorheic area surrounded by North America's Pacific Watershed that includes most of Nevada and Utah) for at least 4,000 years (Wagner and Lebo 1996). Northern Paiutes in the Great Basin or *Numa* organized into discrete bands based on their primary subsidence. According to Wheat (1977), Paiutes followed a seasonal migration pattern over Great Basin deserts in search for food. Pyramid Lake Paiutes remained close to Pyramid Lake during winter and early spring to fish for trout and hunt birds migrating along the Pacific Flyway. During May, other Paiute tribes traveled to Pyramid Lake to participate in the annual cui-ui spawning and celebration (PLPT and USDA NRCS 2005). Cui-ui fish would be gathered and dried for future uses. In the summer and fall, Pyramid Lake Paiutes traveled in search of roots, seeds, and berries and hunted marsh ducks close to water sources (Wheat 1977). The autumn pine nut harvest was an important cultural event for the tribe and after traveling to the best harvest site, they performed ceremonies like the pine nut prayer dance and participated in betting games with other Paiute tribes. Pine nut harvests continued through the fall, as tribal members followed pine nut ripening into the mountains. Usually in November, community rabbit drives were held in desert grasslands. After the harvests were completed, families returned from the mountains to participate in rabbit hunts (Wheat 1977).

In 1859, the Bureau of Indian Affairs (BIA) set aside a reservation for PLPT. Many tribal members adapted to the loss of their livelihood by finding work in white settlements. The settlers established ownership over ancestral Paiute lands, further limiting the customary seasonal migration. Some cultural practices, such as rabbit drives, duck hunting, and gathering of nuts, roots, seeds, and berries, were lost due to non-tribal settlement and exploitation. However, PLPT's cultural values continued to center around Pyramid Lake and tribal land, and basketry remained a symbol of native identity among many tribes. Today, modern cultural values and social networking through pow-wows, ceremonies, and rituals also represent tribal social assets.

4 Results for socio-economic vulnerability factors

4.1 Internal factors

In our analysis, internal socio-economic vulnerability factors for PLPT were well captured with livelihood assets (or capitals) and can broadly explain general adaptive capacity at the community or household level, and thus could be considered for describing vulnerability to climate change.

4.1.1 Education and employment

Education, economic wellbeing, and diversification of livelihoods are important indicators of adaptive capacity (Adger et al. 2004). Our survey showed that the education and economic wellbeing of PLPT members is slightly better than the overall national average for Native Americans (from the U.S. Census 2010, 34 % of PLPT members surveyed attained a 2 or 4 year college degree versus 23 % of Native Americans) and PLPT's degree attainment rate is close to the mainstream U.S. (38 %). Although PLPT's subsistence historically was based on fishing and collecting foods (Interview), in the current context, such subsistence is impractical due to changing tribal lifestyles and values and is replaced by economic opportunities on and off the reservation. The primary source of employment in Nixon (where 25 % of tribal population resides) is tribal government or agriculture while in Sutcliffe (with 15 % tribal population), employment is recreation and small commercial enterprises. The most populated community, Wadsworth (with 50 % of tribal population), is close to Fernley and Reno and is PLPT's commercial hub (PLPT and USDA NRCS 2005). Interviews suggest that there are limited opportunities to diversify household/personal income due to the lack of economic growth and opportunities on the reservation.

4.1.2 Climate change perceptions

About 80 % of the surveyed PLPT members were aware of climate change and observed changes in their environment. About 73 % of respondents believe climate change is happening and 73 % also believe that humans play a role in climate change. This contrasts to the generally low belief (63 %) of climate change and human role (29 %) among other rural Nevada groups and the nation (36 %; Borick and Rabe 2010). In addition, a much larger percentage of respondents (93 %) expressed their priority for climate change action at the national level compared to rural Nevada (16 %) and the nation (54 %, Leiserowitz et al. 2009). Similarly, tribal environmental managers and leaders were overwhelmingly aware of climate change issues. Climate change awareness and traditional ecological knowledge are key to successful adaptation (Wall and Marzall 2006, Hardison and Williams, this issue; Whyte 2013).

4.1.3 Institutional capacity

Administrative tribal resources and knowledge were reviewed to assess adaptation potential including existence of management plans such as natural resources management, disaster risk reduction planning, and prior experience with climate change adaptation/vulnerability studies. Tribal managers and leaders were knowledgeable in science-based natural resource management and collaborated with academic, research, federal, state, and other agencies to conduct research and implement projects. Several management plans were completed and tribal environmental managers were actively involved in their preparation. For example, PLPT developed the Comprehensive Resource Management Plan (CRMP; PLPT and USDA NRCS 2005), which covers planning for all forms of natural resources including wetlands and rangeland. Other available plans include Water Quality Control Plan (WQCP), water system master plan, emergency response plan, and air monitoring plan. Unique among tribes, in 2007, PLPT received Treatment As State Status pursuant to Sections 303 and 401 of the Federal Clean Water Act by the Environmental Protection Agency (EPA) for Program Authority to conduct Water Quality Standards (WQS) and 401 Certification. Since 2008, PLPT had a tribal- and EPA-approved WQCP, which was revised and reviewed extensively for 7 years. In addition, PLPT is involved in the Truckee River Flood Project and implements a conservation and management plan to protect and conserve Pyramid Lake Fisheries. Since 1974, PLPT successfully managed hatcheries and monitored water quality at Pyramid Lake, lower Truckee River, and tribal wetlands. Similarly, PLPT took a proactive approach to monitor invasive species in Pyramid Lake in the wake of Quagga Mussel invasion in Rye Patch and Lahontan Reservoirs. Finally, since 2008, PLPT has been the team lead for water management of the Stampede Reservoir with an objective to ensure long-term viability of the cui-ui, LCT, and Truckee River ecosystem. Although not all environmental divisions in PLPT showed prior experience on climate change vulnerability and related studies, it was clear that there was a strong willingness and common desire among tribal managers to include climate change in their respective programs.

4.1.4 Technology

While not specifically prepared for climate change impacts at present, PLPT has strong potential for climate change adaptation and integrating improved technology, however, the tribe is dependent on federal support which is extremely limited and underfunded (e.g., Indian Health Service). For example, in 2010, only 0.007 % of the fund states received from U.S. Fish and Wildlife Service (FWS) was available competitively to 565 federally recognized tribes. Similarly, in 1999, BIA reported $356 million of unmet tribal natural resource management and in 2012, tribes requested $8.75 million for DOI Climate Change Adaptation Initiative but only $200,000 was planned to be available. Nonetheless, PLPT has a solid tribal administration that is capable of implementing climate change adaptation programs with appropriate support. Existing collaborations and network with universities, research institutes, federal organizations, and other non-profit groups can help develop solutions for climate change impacts and integrate innovative technology. This network has already contributed to building tribal scientific capacity and has supported tribal administration in several environmental and resources management projects.

4.1.5 Physical capital

PLPT's physical capital was assessed to determine potential adaptive capacity to climate change. For PLPT, DOI is largely responsible for basic infrastructure on the reservation while several other federal agencies like EPA and U.S. Army Corps of Engineers have contributed to water quality management and flood control respectively. There were no specific infrastructure to deal with potential climate change, but several types of infrastructure meant for climate variability appear to contribute to adaption potential.

First, PLPT operates five hatcheries to maintain cui-ui and LCT populations in Pyramid Lake and the Truckee River and provide a cushion during drought years. They are: 1) Big Bend Hatchery in Wadsworth, NV to incubate and release larval cui-ui to a wetland area along the Truckee River; 2) Numana Hatchery 8 miles north of Wadsworth along the Truckee River to raise LCT from fry to fingerling size; 3) Dunn Hatchery on the west shore of Pyramid Lake in Sutcliffe, NV to incubate LCT eggs; 4) Koch Cui-ui Hatchery in Sutcliffe to raise endangered cui-ui to supplement lake population; and 5) Lake Operations Facility in Sutcliff to artificially spawn, acclimate, and stock LCT. Similarly, reservoir storage that is dedicated to 'fish' use also enhances the adaptive capacity of PLPT.

In the three PLPT tribal communities, varying water challenges exist and water infrastructure influences adaptive capacity. In Sutcliffe, arsenic contamination and lack of alternate water sources is an urgent issue (PLPT and USDA NRCS 2005). In Nixon, poor water distribution networks are a major concern. In Wadsworth, rapidly a growing population and increasing water demand is a major challenge, thus, a lack of consistent supply of drinking quality water is an issue. However, Wadsworth's de-centralized water systems is a positive aspect of water management because such systems impart flexibility and exhibit economic and environmental sense (Pahl-Wostl et al. 2007), thus contributing to better adaptive capacity to climate change.

Finally, agriculture is inadequate to support farmers' livelihood because of the lack of ownership, financial capital, and farm insurance; relatively small agricultural plots; and presence of invasive and noxious weeds. This results in seeking alternative sources of income. Climate change can impact agriculture through increased invasive and noxious weeds and increased flooding can put pressure on marginal farmers.

4.1.6 Economic resources and financial capital

Pyramid Lake, through recreational activities such as fishing and camping permits, contributes approximately 60 % of internal tribal revenue. Ranching and agriculture were also reported to contribute income to some tribal members and are cultural practices for many. Both survey and interviews revealed that the tribe's most crucial natural asset is Pyramid Lake. The prospects of geothermal and other solar energy projects on the reservation, and more importantly, potential use of the Truckee River Operating Agreement (TROA) settlement fund for PLPT's economic development show some prospect for a diversified economy and may enhance the adaptive capacity to cope with climate change. However, energy opportunities are largely unexplored and uncertain and the economic development fund is tied to TROA implementation, which remains uncertain due to legal hurdles.

4.1.7 Social capital

While governance, institutions, and networks are generic indicators for adaption to any shocks or stresses, they are also useful indicators for climate change adaptation. PLPT has a democratic governance structure and election process. The tribal governing body (tribal council), consists of 10 members elected bi-annually, including eight tribal council members, a tribal chair, and a tribal vice-chair. The household survey revealed that 72 % of surveyed tribal members participate in tribal voting. Similarly, public participation with various level of consultation appears to play a major role in key issues. For instance, in the mid 1980's, the California-Nevada Interstate Compact settlement was subjected to tribal referendum and subsequently, tribal support to the compact was withdrawn (Wilds 2010). In 2008, TROA was also set for tribal referendum before PLPT legally accepted it. Issuance of public information notices on various aspects of environmental management and administration is a common practice for PLPT. The tribal council's decision-making is based on voting; yet there is a consensus on safeguarding tribal interest and entitlement. There are several active religious and social organizations that show potential for emergency mobilization under extreme events or disasters. Interviews revealed that emergency response occurred in the aftermath of the 1997 flooding (a 117-year flood event). Another positive factor demonstrating PLPT's adaptive capacity was the presence of external networks for climate change related studies and knowledge. As mentioned, the PLPT administration (various divisions) has developed a good external network with several entities. This network appears to provide effective consultation or building capacity for climate change adaptation planning. Additionally, PLPT has maintained a strong network with other tribal nations and their consortiums which can potentially enhance its adaptive capacity. However, there were concerns that PLPT members appear to be progressively leaning towards individualism at household and community levels. Elders are socially respected, but they do not have any formal position or power unless elected to tribal council. Intergenerational segregation can put the older generation at risk and individualism can collectively lead to reduced risk sharing and adaptive capacity.

4.1.8 Natural capital

Key indicators contributing to adaptive capacity related to natural capital include biodiversity and conservation of natural resources. The lake and fisheries are the major natural resources on the reservation. Both groundwater and surface water also contribute to tribal water resources, and there is potential for geothermal and solar energy development. Presence of rangelands, wetlands, and agriculture (although small) shows there is some level of diversified natural resources. While conservation does not appear to be a key issue at present (given relatively small population) and priority (e.g., irrigation), tribal administration appears to understand its role. Water conservation plan with price incentives for water conservation and installation of water meters were identified in Comprehensive Resource Management Plan (CRMP), amid concerns of decreasing water supply. In addition, increasing presence of invasive species such as noxious weeds, insect pests, and bullfrogs were additional sources of concern to the tribe (PLPT and USDA NRCS 2005). Nevertheless, the awareness and ongoing initiatives in invasive species control in collaboration with other agencies shows PLPT's strong resource management potential.

4.2 External factors

In our analysis, the external socio-economic vulnerability factors were linked to social, economic, legal, and environmental processes that include and extend beyond the system. As a downstream user, PLPT's vulnerability also depends on political and legal power and other stakeholders (e.g., state and federal). Similarly, as many conflicts are settled in court, judicial decisions have strong control over socioeconomic vulnerability factors.

4.2.1 Federal support and entitlement

As economic development on tribal lands is a relatively new concept, tribes are largely dependent on federal support. Under the federal "trust responsibility," the federal government is mandated with fiduciary duty towards federally-recognized Native American tribes. With such duty, the BIA supports several basic infrastructures such as education, health, and roads. Institutional support by several federal agencies (e.g., EPA and FWS) has been crucial to PLPT in its quest for water rights and ecological protection. Thus, tribal capacity to adapt to climate change may hinge largely on federal support and reduce their adaptive capacity. Federal support can buffer the impact of climate change on tribes, but any economic downturn under climatic or non-climatic stressors might influence the DOI budget and reduce federal support to tribes. In the past, DOI experienced budget cuts and subsequently reduced tribal programs. Such reduction on federal budget can lead to further stress on already underfunded health services (Roubideaux 2002), especially under climate change impacts (Doyle et al., submitted for this issue).

4.2.2 Power relation and legal stressor

Native American reservations are nested within states and thus share and compete for natural resources with other resource users. While entitlement and access to resources can greatly determine the ability to adapt, there may be legal or institutional barriers that impede tribal entitlement and access to resources. Historically, under Orr Ditch Decree Rights of 1944, PLPT's share of water rights was limited to senior irrigation water rights of 14,742 acre-feet. On the contrary, Newlands Project (agriculture in Fernley and Fallon) received the majority of the senior water rights and water was diverted from Derby Dam, largely impacting Pyramid Lake fisheries and tribal livelihood. Tribes went through relentless legal battle for water rights for fisheries and succeeded to forge a win-win relationship with Truckee Meadow Water Authority. While this success appears mostly attributed to Endangered Species Act (ESA) and listing of cui-ui as endangered species, factors including tribal leadership, exemplary relentless legal fighting, and negotiation helped them protect their water rights for Pyramid Lake. At present, PLPT owns storage for 'fish water' in Stampede Reservoir. This storage has enhanced tribal adaptive capacity to climate change impacts to Pyramid Lake fisheries and ecosystem. Upstream storage for fishery purposes will be further enhanced by TROA reservoir operating policies if and when they are approved for implementation by the courts.

TROA provides a detailed but complex framework for reservoir operation imparting flexibility on water sharing under climatic variability (Doremus and Hanemann 2008; Wilds 2010). It has several storage allocations for droughts, municipal and industrial, fish, water quality, and other purposes. The severity of regional drought impacts on Pyramid Lake fisheries depend on drought frequency and duration, lake inflow and water level, predator–prey relationship, water quality, and other environmental variables. Thus, a detailed understanding of potential impacts on cui-ui requires a comprehensive study using the TROA reservoir operation model coupled with a rainfall-runoff (watershed) model in both Truckee and Carson River basins.

4.2.3 Job opportunity and migration

Historically, tribes persevered through small climatic variations by employing adaptation strategies like diversification of food and other resources, innovative technology, rich traditional ecological knowledge, and peripheral temporary migration. They responded to bigger climatic extremes through large-scale migration, replacement of subsistence, and sociopolitical structural changes (Weiss and Bradley 2001). However, in the current context, migration is largely limited to individuals due to internal and external socio-economic pressures and a permanent tribal reservation (Cozzetto et al. 2013). Despite problems of eroding social capital, one potential positive contribution towards future climate change adaptation option at individual level is the presence of employment opportunities in urban areas. Due to limited economic opportunities, employment related migration is common among many tribal members and the survey showed 25 % working off reservation. Thus, in the event of stresses from climate change and impact on current livelihood in the reservation, the existing practices of off-reservation employment can enable adaptation at the individual level.

5 Discussion

Our qualitative assessment of PLPT's vulnerabilities to climate change reveals several contributing elements. External socio-economic factors and processes greatly influence tribal adaptive capacity. Federal support enhances adaptive capacity at individual and reservation level and economic opportunities at Reno-Sparks does the same at the individual level. Climate change appears to bring several challenges to PLPT through impacts to the watershed, rangeland, lake, and ecosystem services. We argue that biophysical vulnerability to climate change on tribal land appears to be strongly modulated by external socioeconomic factors such as non-climatic stressors (e.g., legal, water sharing, population increase and urbanization within tribal land) which can amplify climatic impacts.

Literature suggests that effectiveness of local level processes on adaptive capacity is constrained by larger scale economic and political processes. For instance, Adger et al. (2005) argued that farmers' adaptive capacity to grow crops successfully through enabling local-scale social and physical factors is constrained by macro-scale economic processes that determine crop prices. Such importance of broader processes is quite apparent in PLPT's case. While there are quite favorable internal social and political factors for PLPT, direct and indirect dependence on external factors such as state and federal governmental policies largely constrains tribal adaptive capacity.

The interdependence between PLPT reservation and Reno-Sparks is apparent. While both the lake and reservation are linked with upstream Truckee River Basin, there is also a rural–urban network operating between the reservation and Reno-Sparks. This network has a very strong influence on the physical, social, and economic processes influencing tribal vulnerabilities and adaptive capacity. Proximity to urban centers can provide opportunities for economic development for tribes; nevertheless, they can also impact the ecological integrity of both lake and land based ecosystem on the reservation (e.g. upstream impacts on water quality and quantity) and can be modulated under climate change scenarios. Thus, upstream-downstream interaction should be analyzed and it should be ensured that the ecosystems are not stressed to a level limiting potential for the ecosystem to self-organize (Folke et al. 2004).

Any climate change adaption in the upstream urban region needs to be framed in a collaborative, broader watershed context, to avoid any negative externalities leading to PLPT's reduced adaptive capacity downstream. A positive factor is the increasing collaboration between Truckee Meadows Water Authority and PLPT administration in Public Law 101–618 and TROA settlements and among multiple stakeholders in various federal planning and management activities in Truckee River Watershed. In our detailed analysis of historic accords, conflicts and negotiations, we noticed that PLPT has progressively gained power through relentless legal battle, negotiation, and successful leadership and has emerged as a key player.

Studies have shown that adaptive capacity can also be created (Lemos et al. 2007) through creation, distribution, and communication of knowledge; encouragement of institutions to learn and incorporate changes; and empowering people by raising income and education. This requires investment in people and on processes such as good governance and practices that promote better institutions and address socio-economic inequalities. In PLPT's case, there are several positive attributes at the institutional level including awareness and willingness to adapt. PLPT's proactive natural resource management activities have strong potential to lead to better climate change adaptation for natural ecosystems in the reservation. Another positive factor is the presence of external knowledge, as well as support networks, local awareness of climate change and local values, and trust in the ecosystem approach to natural resources management. Nevertheless, there is an absolute need to empower people through better income and education. While it may be possible to have a strong institutional adaptive capacity for climate change adaptation, the locals may be largely constrained due to socio-economic conditions and declining social networks. While several indicators contribute to the tribal adaptive capacity positively, lower socio-economic status at household and individual level and lack of a self-sustained economy on the reservation appears to counteract other positive factors contributing to tribal adaptive capacity.

Tribes perceive their adaptive capacity as high in a broader perspective due to pride and understanding of how Native Americans have emerged through many historic difficulties and survived over thousands of years adapting to natural and socio-political changes. Their understanding of the environment and the changes on which their livelihood depend inherently give them individual survival skills and confidence that Native American tribes will adapt under climate change (IPCC 2007). This optimism can be constructive but needs to be supported with cautious and prudent planning for the future. Moreover, there are subjective questions regarding the relationships between climate change impacts, culture, and traditional values. The present day context provides several challenges for Native American tribes. While there are broader safety nets through federal programs presently supporting tribes, the inadequacy and inherent uncertainties regarding continued support are paramount. This invokes a need for bottom-up initiatives regarding socio-economic development to enhance present as well as future adaptive capacity. Factors contributing to both present and future adaptive capacity have been emphasized considering potential trade-offs between these two (Folke et al. 2004).

Besides social, there may also be physical and technological limits to adaption (Adger et al. 2009). Under climate change, there may be surprises besides gradual change, (Kane and Shogren 2000), which together with a complex web of interacting external and internal factors may hinder the ecosystems' ability to adapt. For instance, rangeland and wetlands have already been stressed by present and past droughts on the PLPT reservation. While under existing climatic variability, Pyramid Lake fisheries and ecosystem may adapt, the case may be different under unexpected or unexpectedly rapid climate change. Another issue is the speed of climate change – tribes have always lived in dynamic climates, but how people and ecosystems adapt is influenced by the pace of change, as well as the magnitude.

6 Conclusion

PLPT's vulnerability to climate change is tied to a cultural and economic dependence on Pyramid Lake, while external socio-economic factors influence adaptive capacity and amplify potential impacts. To PLPT, the sustenance of Pyramid Lake ecosystem is extremely important for economic, spiritual, and cultural reasons and this is reflected in the fact that cui-ui, the lake, and people are considered the three central components of tribal identity. As a result, PLPT has been persistent in a successful legal battle to obtain water rights and storage for fisheries which will be enhanced by TROA reservoir operating policies if and when courts approve its implementation. Climatic and non-climatic impacts threaten the endangered cui-ui fish by decreasing water quantity and quality. However, an integrated analysis that merges biophysical and socioeconomic vulnerabilities using model driven (top–down) and local perception-knowledge driven (bottom–up) is needed to precisely quantify these impacts and uncertainties. Despite limited economic opportunities and dwindling federal support, PLPT's adaptive capacity to climate change is strengthened by sustainability-based values, technical capacity for natural resource management, proactive initiatives for invasive-species control, strong external scientific networks, and a remarkable awareness of climate change. Like many tribes, PLPT would benefit from increased federal funding for tribal climate change programs, and its resilience would be enhanced by selective sustainable economic development that is sensitive to the relatively unique context of PLPT.

Acknowledgments We express our sincere gratitude to Chairman Wayne Burke, Vice-Chairman Mervin Wright Jr., Environmental Department Manager John Mosely, Former Fisheries Director Dan Mosely and Pyramid Lake Paiute Tribe and Tribal Council. Without their support the study would have never been completed. We acknowledge the support of NSF Nevada EPSCOR seed grant (#EPS0814372). We acknowledge support of Janine Winnemucca in administering household surveys and Kiersten Miranda in conducting interviews.

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DOI 10.1007/978-3-319-05266-3_8
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0746-z

The impact of climate change on tribal communities in the US: displacement, relocation, and human rights

Julie Koppel Maldonado · Christine Shearer · Robin Bronen · Kristina Peterson · Heather Lazrus

Received: 13 November 2012 / Accepted: 17 February 2013 / Published online: 9 April 2013

Abstract Tribal communities in the United States, particularly in coastal areas, are being forced to relocate due to accelerated rates of sea level rise, land erosion, and/or permafrost thaw brought on by climate change. Forced relocation and inadequate governance mechanisms and budgets to address climate change and support adaptation strategies may cause loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment and injustice. Sovereign tribal communities around the US, however, are using creative strategies to counter these losses. Taking a human rights approach, this article looks at communities' advocacy efforts and strategies in dealing with climate change, displacement, and relocation. Case studies of Coastal Alaska and Louisiana are included to consider how communities are shaping their own relocation efforts in line

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

J. K. Maldonado (✉)
Department of Anthropology, American University, Washington, DC, USA
e-mail: jkmaldo@gmail.com

C. Shearer
Department of Sociology, University of California at Santa Barbara, Santa Barbara, CA, USA
e-mail: cshearer@cns.ucsb.edu

R. Bronen
Alaska Institute for Justice, University of Alaska Fairbanks, Fairbanks, AK, USA
e-mail: robin.bronen@akimmigrationjustice.org

K. Peterson
Center for Hazards, Assessment and Response Technology, University of New Orleans, New Orleans, LA, USA
e-mail: krajeskipeterson@msn.com

H. Lazrus
NCAR Earth System Laboratory, National Center for Atmospheric Research, Boulder, CO, USA
e-mail: hlazrus@ucar.edu

with their cultural practices and values. The article concludes with recommendations on steps for moving forward toward community-led and government-supported resettlement programs.

> We are historically fishermen and trappers. We have maintained this life well for hundreds of years, probably longer. Now our waters are contaminated by the industries that increase Global Warming and the layer of pollution in the atmosphere, which brings with it an increase in storms that has led to salt water intrusion of our lands. This is also destroying the vegetation that has been plentiful and abundant for generations, destroying the opportunity for us to be a self-supporting people and to share our bounty with the rest of the planet.
> —Member of Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Indians (Louisiana Workshop 2012)

1 Introduction

Climate change impacts, such as sea level rise, are predicted to displace millions of people around the world, as places become either temporarily or permanently uninhabitable. In particular, people living in coastal and low-lying areas increasingly face the reality of displacement (IPCC 2007; UNDP 2007/2008). In confronting this reality, indigenous peoples have many successful and creative adaptation and mitigation strategies to share (e.g., Cochran et al. 2013; Hardison and Williams submitted this issue; Nakashima et al. 2012; Wildcat 2009). This article highlights some of these strategies in the case studies below, while also discussing how policy changes, past US government efforts with relocation, and international human rights law could assist tribal relocations due to climate-induced changes.

Entire tribal communities in Alaska, Louisiana, and the Pacific Islands, among others, are being forced to relocate due to accelerated sea level rise, erosion, extreme weather events, and/or permafrost thaw, as well as a lack of resources to cope with these impacts in-situ (Callaway et al. 1999; McLean et al. 2009; Louisiana Workshop 2012). In the United States, as well as globally, communities facing the likelihood of relocation are also often those that have experienced systemic impoverishment and injustice, such as coastal tribes of Alaska and Louisiana. This holds significant human rights implications, as tribal communities are among those that are least responsible for causing climate change, are often subject to harm by powerful forces such as oil companies that are responsible for proliferating climate change, and their lands, resources, and culture stand in direct threat or being lost or severely diminished due to climate change impacts (Oliver-Smith 2011:162; UN 2007). Climate-induced displacement does not only sever the physical ties and rights indigenous peoples have to their land and resources, but also the spiritual relationship they have with their traditionally-occupied places (UN 2007). Climate change and its impacts reflect Farmer's discussion of human rights violations as "symptoms of deeper pathologies of power" (2003:7).

Today's capitalist-based social and economic processes have severe consequences for communities' adaptive capacities, shaping their social vulnerability, which is defined as "a combination of factors that determine the degree to which someone's life and livelihood is put at risk by a discrete and identifiable event in nature or in society" (Blaikie et al. 1994:9; also Oliver-Smith 2004:24). Understanding vulnerability as a long-term process means understanding the conditions, such as poverty, political disempowerment, and economic oppression that create barriers to adapting to environmental changes (Hilhorst and Bankoff 2004; Wisner 2004). As Piguet et al. point out, climate change does not take place in a vacuum, but is embroiled within issues of inequality and human rights (2011:25).

For indigenous communities, climate-induced relocation cannot be separated from the sensitive history of government-mandated tribal relocations that occurred throughout the United States from the late 1700s well into the 20th century. The 1830 Indian Removal Act forcibly relocated Native peoples living east of the Mississippi River to a designated place to the west. Along the "Trail of Tears", tens of thousands of Natives lost their lives (Bartrop 2007:185). Indian Removal went beyond physical loss of life; the US policies of dispossession, removal, and reservation boundaries led to loss of cultural identity (Bartrop 2007:184). For example, the lands the Choctaw were moved to in the West became known as "the Land of Death" (Akers 1999:73).

Forced relocations have continued into recent times. For example, in Alaska, Aleut communities were compulsorily moved during World War II (Hesse 2005). These relocations, as well as the consolidation and settlement of Alaska Native tribes during the 20th century because of the government mandate to attend school (Shearer 2011), has limited the ability of tribes to draw upon their traditional knowledge in adapting to a rapidly changing environment.

In the contiguous 48 states, tribes experience increased vulnerability to changing weather patterns and climate impacts due to loss of traditional subsistence practices resulting from the history of reservations and western land expansion. As opposed to how Natives once moved from place to place as needed for food and safety, those on reservations have limited options because of restrictive reservation boundaries (Lynn et al. 2013), similar to the populations of low-lying island countries that are constrained by geographic and political boundaries (Lazrus 2012). Federal laws obstruct expanding or transferring tribal jurisdiction and few tribes have the economic means to buy new land. Therefore, tribes' traditional cultures are directly threatened by current and future climate change impacts (Houser et al. 2001:357). For coastal communities, there is now the added complication that many coastlines are destabilizing from erosion, sea level rise, and/or permafrost thaw, further limiting their relocation options and complicating their dependence on living near water to meet subsistence needs.

Forced relocation is compounded by the current lack of governance mechanisms or budgets to support the communities, which intensifies community impoverishment, negative economic and health impacts, and loss of place, social networks, and culture (Bronen 2011:360). Kivalina and Newtok in Alaska and Isle de Jean Charles in Louisiana are three of the communities facing similar issues and leading their own relocation efforts, and in doing so are trying to forge needed policies for relocation.

2 Case studies

Kivalina and Newtok, Alaska, and Isle de Jean Charles, Louisiana, are examples of tribal communities in the US that share a common fight to save their culture, ancestral land, and communities in the face of both the causes and effects of climate change. All face permanent displacement from climate-related stressors, and although their situations differ, they face many of the same challenges in achieving their safe relocation.

2.1 Kivalina

The Native Village of Kivalina lies approximately eighty miles north of the Arctic Circle, on the tip of a thin, six-mile long barrier reef island of 27 acres (11 ha). Its population of about 400 is primarily Inupiat, tracing their ancestry in and to the area for thousands of years. Their experience offers an example of a tribal community attempting to pro-actively adapt to climate change while being constrained by existing policies—policies that, by their design, have largely channeled assistance and funding toward remaining on the existing settlement rather than relocating.

Kivalina was originally used as a seasonal hunting ground but, in 1905, tribal parents were ordered by the US Bureau of Indian Affairs to enroll their kids in school or face imprisonment, thus beginning the stationary settlement on the island (Shearer 2011). This settlement depended on the formation of sea ice in early fall, hardening the island and buffering it against storms. With warming Arctic temperatures, the ice now forms as late as November or even December, leaving the shoreline exposed and vulnerable to erosion (GAO 2003).

Kivalina residents first noted coastal erosion in the 1950s and formally voted to begin a relocation process in 1992 (Mitchell 2007). This was later supported by a 2003 Government Accountability Office report stating that most of Alaska's more than 200 Native villages were affected to some degree by flooding and erosion, in part due to rising temperatures, with 31 facing imminent threats and four requiring relocation, including Kivalina (GAO 2003). A 2006 Army Corps assessment estimated that the village of Kivalina, as well as Newtok and Shishmaref, would be lost to erosion in 10 to 15 years, with an estimated relocation cost of US$80 million to US$200 million for each village (USACE 2006).

Rock revetment project under construction, Kivalina 2008. Source: Christine Shearer

As Kivalina residents tried to relocate, however, they found that there was no designated government body to assist communities with the process, and that many disaster programs and funds are available only after a disaster occurs, limiting the ability of both the relevant US government agencies and Kivalina residents to begin relocation (Shearer 2012a).

Kivalina's at-risk coastal situation became dangerous in 2004 and 2005 when big storms hit the tiny island, eroding the coastline and putting several homes in danger (Shearer 2011).

Government reports later estimated the village had experienced between 70 to 80 ft of erosion from the storms, in some areas exposing the permafrost (USACE 2007).

Kivalina was declared a disaster area and the Federal Emergency Management Agency (FEMA) provided sandbags to help prevent further erosion. In 2005, Congress passed Section 117 in the 2005 Consolidated Appropriations Act, which allowed the Army Corps to carry out storm damage protection projects for Alaska Native Villages at full federal expense (GAO 2009). A sea barrier was constructed for Kivalina by a private Department of Homeland Security contractor; the barrier failed the day before its inauguration, leaving the village temporarily unprotected (Shearer 2011).

After an evacuation from another storm in 2007, the Army Corps approved construction of a large rock revetment project for Kivalina. Despite the revetment, community relocation remains necessary. Yet no agency has complete responsibility for relocation, and there are few policies and protocols in existence to legally move the process forward. Instead, there are multiple agencies with different authorities, norms, and responsibilities, which Kivalina residents must try to bring together through their own efforts (Shearer 2012a). In addition, there have been disagreements over the new relocation site and tribal knowledge between Kivalina residents and government agencies and contractors, which has further slowed the relocation (Shearer 2011).

2.2 Isle de Jean Charles

The Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Indians was historically a fishing, trapping, and hunting community in Terrebonne Parish, Louisiana. Forcibly displaced from their original lands by European settlers, the Isle served as a refuge for Natives to escape to the end of the bayous in dense forested swamps to avoid being forcibly relocated or killed. Today, the communities' culture and water-based settlements and livelihoods are threatened by both the causes and consequences of climate change.

Flooding on Isle de Jean Charles, Hurricane Isaac 2012. People raise their homes to adapt to land loss and rising waters. Source: Julie Maldonado

In the 1950s, the Isle was about 5 miles by 12 miles; today it is approximately 1/4 mile by 2 miles, due to intense coastal erosion and saltwater intrusion. The diminution was initially influenced by oil and gas companies such as Texaco dredging canals and cutting thousands of miles of pipelines along Louisiana's coast. In addition, the construction of dikes and levees, damming of the Mississippi River, other flood control measures, and large-scale agricultural development prevent sediment and silt from reaching the delta, leading to subsidence (Button and Peterson 2009; Freudenberg et al. 2009; Laska et al. 2005).

Climate-induced sea level rise now threatens the community. Coastal Louisiana has experienced one of the highest rates of relative sea level rise in the world, with an over 8-in. rise in the last 50 years (Karl et al. 2009). Relative sea level rise could be the tipping point beyond which restoration is impossible.

With severe loss of wetlands and barrier islands to the south, the Isle no longer has natural protection against hurricanes and storms; it is now the storm buffer for communities to the north. Since 2005, the Isle has survived six major storms. While the Isle rarely experienced flooding from hurricanes before, the Isle now floods during high tide. Many of the Isle's trees, traditional and medicinal plants, gardens, and trapping grounds are gone (Louisiana Workshop 2012). There were 78 homes in 2002, but only about 25 remain by 2012. The community also continues to experience health and livelihood impacts from decades-long industrial contamination and encroaching toxic industries, chemicals from dispersants, oil spills, including the 2010 BP oil disaster, and post-storm debris contaminating the air, soil, and water.

Additionally, the community continues their efforts to receive tribal federal recognition, which they have thus far been denied based on historical injustices, such as being pushed to the end of the bayous by European settlers and forcing them into isolation, which makes it difficult to prove a sustained political authority and descent from an historical tribe (Miller 2004). This struggle is significant to their vulnerability because federal recognition would give them specific benefits and protections, such as "the necessary bargaining power when confronting the Corps of Engineers in their struggle for inclusion [in the Morganza-to-Gulf project]" (Katz 2003:3–4).

State reports have concluded that, if nothing is done, the Isle will be gone before 2050 (Coastal Protection and Restoration Authority of Louisiana 2012). Despite this, the community is omitted from coastal restoration efforts, including the Army Corps' Morganza-to-the-Gulf-of-Mexico Hurricane Protection Project and is given minimal attention in Louisiana's 50-year Master Plan for Coastal Restoration because the authorities claim that extending protection to the community does not meet required cost-benefit analyses (Coastal Protection and Restoration Authority of Louisiana 2012). The political decisions that determine who gains and loses from such cost-benefit analyses, legitimized by government and project authorities, need to be critically considered to understand the underlying implications of who is being sacrificed for the greater common good (Roy 1999). Attempting to explain the harm caused to individuals and communities by claiming the greater benefit to all, cost-benefit analysis is entirely insufficient because it does not include the distribution of costs and benefits and completely ignores important social and cultural factors, instead only considering economic impacts (Cernea 2000:3671; Mayo 2010).

As a result of these various stressors, the Traditional Chief and others are working to relocate together those who have scattered and those who would like a communal safe haven, while still working to save their ancestral land. As he explained, "[p]eople want to come back to the community. We have to come together to make sure the land belongs to us while we move to a safe location" (Louisiana Workshop 2012). Community leaders pushed for relocation in 2002 through the Army Corps of Engineers, and again in 2009, but ran into regulatory challenges of relocating an entire community without internal and little external funding. They are looking not just for community and cultural restoration but also for traditional livelihood development to once again be a self-sustaining community.

Without government support, the Isle community, as others have, is taking the initiative to determine their future and lead their relocation. In 2010, following the BP disaster, representatives of Newtok, Isle de Jean Charles, and other Louisiana and Alaska at-risk coastal communities came together through the work of an academic center and a religious congregation to develop people-to-people learning exchanges, as well as advocacy through local and national social and political structures and systems. Through these partnerships, they have traveled to each others' lands and communities to learn what each is experiencing and take the knowledge back as advocates on the others' behalf. The communities continue the knowledge exchanges and co-learning based on local, citizen science and traditional ecological knowledge.

2.3 Newtok

Newtok is a Yup'ik Eskimo village located along the Ninglick River near the Bering Sea in western Alaska (Cox 2007). Approximately 400 people reside in 60 homes in the village. No roads leads to or from the village, which is surrounded by one of the largest river deltas in the world. Wave action and thermal degradation of the permafrost-rich riverbank are causing accelerated rates of erosion (Cox 2007).

Six extreme weather events between 1989 and 2006 exacerbated the rate of erosion. FEMA declared a disaster in five of these events (ASCG 2008). These storms repeatedly "flooded the village water supply, caused raw sewage to be spread throughout the community, displaced residents from homes, destroyed subsistence food storage, and shut down essential utilities" (USACE 2008a). Public infrastructure that has been significantly damaged or destroyed due to the combination of extreme weather events and on-going erosion (USACE 2008b), and the 2005 storm also destroyed the Ninglick River barge landing, making it difficult to deliver essential supplies such as fuel.

Newtok permafrost thaw along Ninglick River. Source: Robin Bronen

A new dump site located across the Newtok River from the village, built as a short-term emergency response in 1996, is still in use in 2012 (ASCG 2008). Garbage gathers on the village side of the Newtok River and can only be transported by boat across the river at high tide (ASCG 2008). The lack of a sanitary village landfill and sewage treatment facility is creating a public health crisis for the community. Between 1994 and 2004, 29 % of Newtok infants were hospitalized with Lower Respiratory Tract Infections because of high levels of community contamination and the lack of potable water for drinking and hygiene/sanitation practices (ASCG 2008). Salt water intrusion affects the potable water (Cox 2007).

The State of Alaska spent about $1.5 million to control the erosion between 1983 and 1989 (USACE 2008b). Despite these efforts, severe damage to the community is expected by 2016 (USACE 2006). Erosion of the Ninglick River is projected to reach the school, the largest structure in the community, by about 2017 (USACE 2008a).

Newtok inhabitants voted three times, most recently in August 2003, to relocate to Nelson Island, nine miles from Newtok (Cox 2007). Newtok obtained title to their preferred relocation site, which they named Mertarvik, through a land-exchange agreement negotiated with the US Fish and Wildlife Service (Cox 2007). In 2006, the Newtok Planning Group, an ad hoc intergovernmental and multidisciplinary working group dedicated to Newtok's relocation and lead by the Newtok Traditional Council, began a strategic relocation planning process. Through their efforts, pioneer infrastructure including a barge landing, six homes and the foundation for an emergency evacuation center have been built. No electric, sewage or water system currently exists at the new site. Due to enormous local, state, and federal legislative and institutional barriers, the relocation is occurring very slowly, but it is moving forward (Bronen 2011).

3 Legal aspects and policy implications

The case studies raise policy and legal implications in the US and internationally, for both the agencies involved in disaster management and the affected communities. No US federal government agency is mandated to manage communities' adaptation efforts in general or relocation efforts specifically, and there are few funds to pro-actively move an entire community. Such an agency could be designated and funded, arguably as part of a stronger emphasis of US disaster policy on risk mitigation, which could serve as a bridge toward climate change adaptation and relocation policies (Shearer 2012b). Indeed, US disaster management and coastal armament was largely structured around a more stable climate that can no longer be assumed.

Many of the problems that Kivalina, Isle de Jean Charles, and Newtok face in relocating are rooted in the lack of a lead federal, state, or local government agency. In the absence of a lead entity, agencies often individually prioritize assistance to villages on the basis of their own agency's protocols and criteria, without an overarching or centralized structure. If there are problems with just one agency, the entire relocation process can be put on hold. A designated federal agency and relocation policy would help coordinate these now dispersed efforts (GAO 2009).

Additionally, federal programs to help threatened communities prepare for disasters are limited and unavailable to many tribal communities. While FEMA administers flood insurance, disaster recovery programs, and grants for disaster mitigation and preparedness, Alaska and American Indian villages often fail to qualify because of their small populations and remote locations, making government-required technical data sparse and cost-benefit analyses prohibitively expensive (GAO 2009). Further, most funding for disasters are triggered after disaster occurs (GAO 2009). Disasters are specifically defined by statute and do not include slow, ongoing climate-induced environmental changes, such as increasing sea level rise, steady erosion, and permafrost thaw (Bronen 2011). In order to respond to these changes, the Stafford Act—the primary disaster relief and response legislation in the United States—needs to be amended so that FEMA can deal with the problems facing affected communities (Bronen 2011).

Most importantly, communities should be empowered to make decisions regarding the most appropriate adaptation strategy to these climate-induced environmental changes (Hugo 2011), particularly given the long history of indigenous experiences with forced relocation (Marino 2012). Whyte (2013) points to the need for institution building to allow for the creation of respectful relationships between tribal communities and government authorities in justly taking actions that include the communities' voice and input.

While agencies and communities are facing new challenges with climate change, community-driven and government-assisted relocation in the US is not without precedent. We now consider the precedent set with the Resettlement Administration in the US, experienced in a time of economic depression, and the lessons learned from development-forced displacement and resettlement worldwide.

4 Lessons learned from past relocations

Following the great Dust Bowl, the epic flood of 1927, and the Great Depression, cities and states made laws against those who migrated to other regions for subsistence (Gast 1934). When squalor conditions in cities became a health and human rights issue (Meck and Retzlaff 2009), In response, President Roosevelt instituted policies regarding relocation and subsistence farms, resulting in a complex network of 100 federally funded multi-dimensional relocation projects across the US (Conklin 1991; Harrison 1952; Holley 1975; Melville 1985; Melvin 1936), bolstered by federal resources, such as land, staff, tools, and education (Roosevelt 1934).

With the Resettlement Administration, multiple government agencies dedicated resources toward successful community relocations, which could help inform the framework needed for climate-induced relocations today. Although the program was not directed to tribal governments, it was directed to populations that were indigent and marginalized, needing to be resettled due to a complexity of circumstances shaping their vulnerability, as is the case with communities in the US facing climate change and displacement today. The resettlements were most successful when community input and participation was integrated and supported, rather than relying upon a top-down bureaucratic structure, as is often the case with resettlement schemes around the world (Hugo 2011). While the people who relocated together did not shape the initial development of the new community, they did have their own council and could make decisions on the community's future direction. For those that still exist, such as Arthurdale and Reidsville in West Virginia, culture and heritage have been preserved where attention and resources were dedicated to the people (Ward 1995). Lessons can be learned from the Resettlement Administration's ability to pull together resources from across federal agencies during the Depression and the positive outcomes brought about by direct community involvement and bringing people together from the local community to government to anthropologists to engineers.

In conjunction with the historical model of resettlement, it is important to learn from past experiences that have demonstrated the disastrous consequences of displacement and resettlement. Negative consequences for the individuals, families, and communities affected by development-forced displacement and resettlement in the 20th century include community fragmentation, health risks, and loss of traditional skills (Cernea 1997; Cernea and Mathur 2008; De Wet 2006; Oliver-Smith 2009a). Development-forced displacement and resettlement schemes have "relevance to climate change displacement, due to destruction of the landscape and which populations are typically impacted, among other reasons" (Hugo 2011:261, 274). Climate change impacts can drastically alter the place people are attached to and these effects cannot just be economically compensated. For tribal communities, "it is more than being connected or attached to the land, we are part of the land, it is part of us and we are part of it.... the water, the air, all of it runs through our veins and souls. To be here is to live, to be elsewhere is to die to who we are" (Philippe 2008).

Patterns found in development-forced displacement and resettlement, such as "bureaucratic inconsistencies, agency contradiction, and planning and procedural rigidities…seem to be part of future scenarios for people facing displacement by sea level rise, unless significant progress in the field is achieved" (Oliver-Smith 2009b:36). Relocation therefore necessitates management and planning though participatory processes and according to communities' needs and priorities, including the relocation site (Farbotko and Lazrus 2012). Addressing responses to climate change impacts in Pacific Island communities, including migration due to rising seas, Farbotko and Lazrus (2012:388) present alternative framings for migration practices that are relevant for communities globally; "[a]s island populations table various alternative visions of future migration, it becomes apparent that equitable climate change governance requires greater openness to islander emotions, values, mobilities and spaces."

Protocols to guide community relocation should arguably be rooted in a human rights framework that asserts and protects communities' rights to self-determination, and helps prevent communities from being forced to disband or move from one at-risk location to another (Bronen 2011).

5 A human rights approach to relocation

No human rights document exists within the US or internationally that protects communities forced to relocate because of climate change (Bronen 2011; Lazrus 2012). Several international human rights documents, such as refugee law and the Guiding Principles on Internal Displacement, provide a theoretical basis for creating these principles. However, none address the complex and unique situation of people forcibly displaced because of climate-induced environmental change (Bronen 2011).

Refugee doctrine is inapplicable because these laws are based on the fundamental principle that a person needs legal protection because they are outside their country of origin due to persecution by a government actor or an actor the government cannot control (Bronen 2011). Yet climate-induced displacement is expected to occur primarily within national borders, as demonstrated in the three case studies given above (Warner et al. 2009). Clear exceptions are populations of low-lying coastal and island countries, such as Tuvalu, Kiribati, and the Maldives (Lazrus 2012). The Guiding Principles on Internal Displacement outline a framework of human rights protections for people who are internally displaced within their country of origin (United Nations 2004). These principles, however, are based primarily on population displacement caused by ethnic and political violence.

Guiding Principles on Climigration have been proposed (Bronen 2011). Climigration is permanent community displacement caused by gradual climate-induced biophysical changes, combined with repeated extreme weather events, which severely impact infrastructure, such as health clinics and schools, and threaten the livelihoods and well-being of the people residing in the community (Bronen 2011). Guiding Principles of Climigration will specifically protect the collective rights of peoples forced to relocate. The right to self-determination is the fundamental principle, which comprises the Guiding Principles of Climigration. The collective right to self-determination ensures that indigenous communities can determine their own identity, belong to "an indigenous community or nation, in accordance with the traditions and customs of the community or nation concerned" and make decisions about internal and local affairs (UN Declaration on the Rights of Indigenous Peoples 2007, articles 9, 33). Affected communities must make the decision that relocation is the only adaptation strategy that will protect them from climate-induced environmental changes and communities must be designated as a key leader in the relocation process. Relocation must be community-based and community-guided.

The Guiding Principles on Climigration will protect the social, economic and cultural human rights, defined in the UN International Covenant on Economic, Social and Cultural Rights (1976), of individuals and communities forced to relocate because of climate change, whether internally or across national borders. These rights must be protected during displacement as well as relocation. For indigenous communities, tribal relationships are essential to cultural identity. Tribes must decide how the community will relocate to ensure that socio-cultural institutions remain intact. Subsistence rights and the customary communal rights to resources must also be affirmed (Bronen 2011).

Relocation must not diminish the living standards of the affected communities. The Guiding Principles on Climigration will affirm the right to safe and sanitary housing, potable water, education and other basic amenities. Embedding these principles in the relocation policy framework will enhance the resilience capacity of communities by addressing socio-economic issues, such as lack of economic development and poverty, which can contribute to communities' vulnerability.

While this article deals primarily with tribes in the US, we acknowledge that communities around the world face similar challenges. As is being experienced in Alaska and along the coast of Louisiana, communities around the world are finding that there are few, if any, channels available to them to carry out risk mitigation, in-situ adaptation, and to begin the conversation about international migration. There are also significant differences between relocation within the US and in the international context, primarily questions about sovereignty (although somewhat parallel to negotiations between tribes and the US government), citizenship, and human rights that arise from crossing national borders. New formulations of nationality and nationhood are required to deal with unprecedented conditions (Burkett 2011). In places like the Pacific Island country of Tuvalu, migration is a way of life and should be "allowed" to be an adaptation to climate change in the future, as it has been historically (Farbotko and Lazrus 2012; Lazrus 2012). We need to expand understandings of migration and adaptation to include managed migration that is carried out according to cultural needs and priorities, as well as broaden shared notions of the nation state, sovereignty, and citizenship.

6 Concluding statement

Climate-induced displacement is bringing new challenges that are particularly affecting tribal populations, as these three case studies illustrate. Yet while anthropogenic climate change may be a relatively new problem, many of the issues it is raising around displacement and relocation are not without precedent. That is why we have used the case studies to examine the implications for policymakers, while also drawing upon lessons learned from development-forced displacement and resettlement and past US efforts toward relocation. Further, tribal communities have a long history of adapting to environmental changes that should be recognized and protected. We therefore argue these efforts should be rooted in a human rights framework that asserts and protects tribal rights to determination and preservation, which could serve as both a national and international model for future displacements. Indeed, traditional tribal methods for adaptation could be used as a basis for informing and enacting future policies as we face increasing challenges from global environmental change.

> One thing that we gain from pioneering is continuing and honoring our values.
> If we rely on the western society's way of life, that's forgetting who I am.
> We need to go back to our way of life. We have to start somewhere.
> —Newtok Traditional Council Member (Agnew-Beck Consulting 2011)

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DOI 10.1007/978-3-319-05266-3_9
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0733-4

Cultural impacts to tribes from climate change influences on forests

Garrit Voggesser · Kathy Lynn · John Daigle · Frank K. Lake · Darren Ranco

Received: 13 November 2012 / Accepted: 17 February 2013 / Published online: 29 March 2013

Abstract Climate change related impacts, such as increased frequency and intensity of wildfires, higher temperatures, extreme changes to ecosystem processes, forest conversion and habitat degradation are threatening tribal access to valued resources. Climate change is and will affect the quantity and quality of resources tribes depend upon to perpetuate their cultures and livelihoods. Climate impacts on forests are expected to directly affect culturally important fungi, plant and animal species, in turn affecting tribal sovereignty, culture, and economy. This article examines the climate impacts on forests and the resulting effects on tribal cultures and resources. To understand potential adaptive strategies to climate change, the article also explores traditional ecological knowledge and historical tribal adaptive approaches in resource management, and contemporary examples of research and tribal practices related to forestry, invasive species, traditional use of fire and tribal-federal coordination on resource management projects. The article concludes by summarizing tribal adaptive strategies to climate change and considerations for strengthening the federal-tribal relationship to address climate change impacts to forests and tribal valued resources.

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

G. Voggesser
Tribal Partnerships Program, National Wildlife Federation, 2995 Baseline Road, Suite 300, Boulder, CO 80302, USA

K. Lynn (✉)
Environmental Studies Program, University of Oregon, 5223 University of Oregon, Eugene, OR 97403-5223, USA
e-mail: kathy@uoregon.edu

J. Daigle
School of Forest Resources, University of Maine, 221 Nutting Hall, Orono, ME 04469-5755, USA

F. K. Lake
USDA Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002, USA
e-mail: franklake@fs.fed.us

D. Ranco
Native American Research, Department of Anthropology, University of Maine, 5773 S. Stevens Hall, Orono, ME 04469-5773, USA

1 Introduction

Climate change impacts, including increased frequency and intensity of wildfires, higher temperatures, extreme changes to ecosystem processes, forest conversion and habitat degradation are threatening tribal access to valued resources (Ryan et al. 2008). Climate change is affecting the quantity and quality of resources—such as water, minerals, and various plants, animals, and fungi—that tribes depend upon to perpetuate their cultures and livelihoods. In addition to providing sustenance, these resources and habitats have proven invaluable to cultural, economic, medicinal, and community health for countless generations.

Climate impacts on forests are expected to directly affect culturally important plant and animal species, in turn affecting tribal sovereignty, culture, and economy (Reo and Parker, submitted for this issue). Observed impacts include species losses and shifts in species ranges (Rose 2010; Swinomish 2010), including northward or elevational migration of some temperate forest species, contraction or expansion of other plant species, and changes in the distribution and population density of wildlife species (Trainor et al. 2009). Loss of biodiversity, impacts on culturally important native plants and animals, increases in invasive species or pathogens, bark beetle damage to forests and increased risk of detrimental wildfires have been observed in the Southwest (ITEP 2011), across much of the West, and in Alaska (Bentz et al. 2010; Hicke et al. 2012; Valachovic et al. 2011).

Increasing wildfires are projected to affect culturally valued resources. Rising temperatures, hotter and drier summers, and wildfires are projected to increase in frequency, intensity, and severity (Moritz et al. 2012; Flannigan et al. 2005). Droughts, as well as tree mortality and vegetation stress, will result in longer fire seasons by increasing fuel loading, insect outbreaks, and the spread of invasive species (NWF 2011). Rising temperatures are projected to affect tree ring growth and vegetation productivity in the Arctic (Andreu-Hayles et al. 2011). And just as climate change stands to affect forests and tribally valued forest resources, forests will play a role in affecting local climate responses (Mote et al. 2003).

This article examines the climate impacts on forests and the resulting effects on tribal cultures and resources. To understand potential climate change adaptation strategies, the article explores traditional ecological knowledge and historical tribal adaptive approaches to resource management, as well as contemporary examples of research and tribal practices related to forestry, invasive species, traditional use of fire and tribal-federal coordination on resource management. The article concludes by summarizing tribal climate change adaptation strategies and considerations for strengthening the federal-tribal relationship to address climate change impacts to forests.

1.1 Traditional ecological knowledge and climate impacts on forests

Climate impacts on tribal cultural resources will affect the formation and use of Traditional Ecological Knowledge (TEK). TEK, the indigenous way of understanding relationships among species, ecosystems, and ecological processes, can play a vital role in climate change assessment and adaptation efforts that bridge human and environmental systems (Whyte 2013; Hardison and Williams, submitted for this issue). Indigenous knowledge systems provide detailed information about ecosystems and spiritual and cultural identity (Grossman 2008; Parker et al. 2006; Turner and Clifton 2007). Native peoples use this knowledge to maintain and cultivate biodiversity, valued resources, and ecological health in their homelands (Jones et al. 2008; Salick and Byg 2007). Simultaneously, people adapt their knowledge base to changes in the environment (First Stewards 2012; Grossman 2008; Swinomish

2010; Turner and Clifton 2007). Many tribes are concerned about how climate change will affect their relationship with culturally significant species and ecosystems. They are also worried about the loss of TEK as climate change creates challenges for Native peoples to observe, experience and understand changes and how to strategically adapt (Parker et al. 2006). The loss of TEK coupled with especially rapid ecosystem alterations or redistribution of species populations resulting from climate change may cause indigenous peoples to become alienated from their traditional landscapes (Swinomish 2010; Turner and Clifton 2007). Many tribes will face challenges in regards to the migration of valued resources due to political and jurisdictional constraints, potentially making them climate refugees in their ancestral territories. Furthermore, climate change may reduce biodiversity in local ecosystems, making it more difficult for native peoples to use traditional adaptation strategies (Salick and Byg 2007).

Unchecked, these challenges threaten tribal cultural resilience and well-being. In response, many tribes are emphasizing greater use of TEK and traditional adaptation methods (Jones et al. 2008; Swinomish 2010). TEK can help inform the dynamics of climate change by "teach[ing] what to look for and how to look for what is important" (Berkes 2009) in terms of ecosystem change. For example, alterations in the seasonality of indicator species (species whose presence or behavior provides information about the state of other species or ecological relationships) make it difficult to understand how other species will behave (Turner and Clifton 2007). TEK and native language may improve understanding of changes in ecological cycles (EPA 2011). When TEK is paired with Western science, a more comprehensive multi-scale strategy may result to better address climate change impacts on tribal cultural practices and traditional lifeways (EPA 2011).

1.2 Tribal adaptation to changing fire regimes and climate

Tribal cultures have adapted their subsistence strategies and socio-economic systems in response to climate and fire regimes for millennia (DeSantis et al. 2010; Moss et al. 2007; Williams 2002). Climate and bio-physical settings (e.g., weather, soils, topography, and vegetation) influence natural fire regimes (Gedalof 2011; Moritz et al. 2011). Tribal peoples observed and adapted to the effects of fire on ecological processes at various scales, from local habitats to landscapes encompassing diverse ecosystems (Nowacki et al. 2012; Stewart 2002).

Fire regime changes are currently being observed in North America (Cohen and Miller 2001). In particular, longer fire seasons and more frequent and severe wildfires are likely to impact cultural use and the availability of tribally valued resources.

In the Pacific West, wildfires have changed elk and deer forage and drought has reduced forage quality (DeVos Jr. and McKinney 2007). In the Midwest, Northeast, and South, changes in seasonal moisture have reduced forest nut crop abundance, stressing food webs and the dynamics of ecosystems utilized by tribes (McKenney-Easterling et al. 2000; Speer et al. 2009).

Fire regimes have evolved in response to natural and anthropogenic influences for millennia (Stewart 2002). Fire regimes directly influence vegetation composition and structure (Falk et al. 2011; Perry et al. 2011). Natural fire regimes differ from cultural fire regimes in that the latter depend on anthropogenic/tribal ignitions (Stewart 2002). There is also a difference between major wildfires in "natural" regimes that may be partially caused by human management and other fires that are not influenced by humans (Kofinas et al. 2010). Cultural fire regimes emerged as a result of time-tested tribal knowledge regarding the effects of climate and fire on culturally valued resources. Tribes utilized fire to increase the predictability of resources, as well as to increase ecosystem resilience. Tribes used fire for crop management, basketry, range-browse improvement, fire proofing around valued resources, clearing travel routes, driving game/prey, clearing riparian areas, increasing water yield, communication/signaling, warfare, and rituals (Stewart 2002; Williams 2002). Tribes still value and apply many of the historical uses of fire today (Mason et al. 2012).

Projected climate change impacts in North America will result in alterations to most U.S. fire regimes, leading to changes in tribal adaptation strategies (Cohen and Miller 2001; Trosper et al. 2012). TEK and tribal practices can inform adaptation strategies to fire and contribute solutions to reduce climate change impacts on ecological services and culturally significant resources.

2 Climate impacts on tribally-valued forest resources

Indigenous peoples are culturally invested in specific values, meanings, and identities that are linked with the natural landscape (Daigle and Putnam 2009). Forest responses to climate change may alter tribal livelihoods and traditions and require unique adaptation strategies to ensure sustained access to tribally valued resources important for tribal economies and traditions.

Climate impacts on forest resources may have direct effects on traditional foods important to tribes (Lynn et al. 2013). Projected changes in climate for California's forest-oak dominated (*Notholithocarpus* and *Quercus* sp.) ecosystems include dryer and warmer conditions in the next 50–100 years (Kueppers et al. 2005). Paleoclimate reconstructions and fire ecology studies show that oaks are resilient to drought conditions and increased fire frequency (Holmes et al. 2008). Despite these adaptive traits, oaks may experience costs in the reduction of acorn-mast production (Pérez-Ramos et al. 2010). As historical tribal burning gave way to fire suppression and exclusion, the increased density of other vegetation has decreased the ability of oaks to resist additional climate-related stress. Precipitation changes coupled with cooler temperatures may predispose oaks to diseases (e.g., exotic pathogen *Phytophthora*), while warmer conditions may predispose diseased or environmentally stressed oaks to greater fire risks (Dale et al. 2001). Reductions in acorn production, coupled with water stress, increases acorn susceptibly to insect damage. Less resilient oak trees, reduced acorn production, increased fire threat and insect pests synergistically combine to make lower quality and quantity of acorns available for tribal and wildlife food consumption.

2.1 Climate-related impacts from invasive species and pests

Climate change will exacerbate the risks posed by invasive species to forest resources (Reo and Parker, submitted for this issue). The threats of urbanization, unsound management, and exotic pathogens (e.g., Sudden Oak Death-*Phytophthora ramorum*) to oak-dominated ecosystems will diminish tribal opportunities to utilize acorns and other food plants (e.g., Evergreen huckleberry, salal, California myrtle) (Ortiz 2008). Unfortunately, few mitigation or adaptation strategies exist for tribal acorn gatherers. Current policies and land management practices do not adequately address tribal concerns (Seppälä et al. 2009; Cordalis and Suağee 2008; Krakoff 2008). To promote production of higher quality acorns, tribes who rely on acorns for ceremonial and dietary uses could work with local land managers to prioritize access and contribute tribal knowledge to the design of restoration treatments.

Compounding climate change impacts to tribes are the multi-scale effects of invasive species as animal and plant pests, pathogens, and diseases directly affect subsistence and ceremonial practices, health and safety. Pests are increasing forest mortality and reducing the quality and quantity of forest products valued by tribes. Pathogens and diseases are affecting habitat quality, plant health, and pose a direct threat to humans (Dukes et al. 2009; Sturrock et al. 2011).

The relationship between invasive species and climate change is increasingly important to understand as environmental changes create more suitable conditions for the spread of invasive species and an acceleration of landscape-level change. Invasive species can outcompete, displace or colonize habitats occupied by native species. Invasive species can alter nutrient, hydrologic, or fire regimes, changing the quality or quantity of valued forest resources. Tribes may be forced to alter subsistence or ceremonial practices in response to the compounded stressors of climate change and invasive species. Specific impacts involve the loss of traditional resources and changes in the geographical range of species. Invasive insects, pathogens and fungal diseases can kill trees valued for food or materials, and restructure the composition, structure and function of forests (Dukes et al. 2009; Sturrock et al. 2011).

Sudden Oak Death, or SOD (*Phytophthora ramorum*), first detected in coastal northern California in the mid-1990s, is now threatening oak-dominated forest ecosystems (McPherson et al. 2010; Valachovic et al. 2011). As SOD spreads, it will diminish tribal opportunities for utilizing forest resources. Many of the pathogen's hosts are trees or shrubs utilized by tribes for foods, materials, and medicines (Ortiz 2008). In addition to the increased mortality of culturally valued plants, heightened fuel loading will elevate the threat of wildfire. As trees and shrubs die, fuel accumulates, threatening life, property and resources. Some current treatments, such as herbicides, used to prevent or limit the spread of SOD (Valachovic et al. 2011) can also degrade tribally valued forest resources (Ortiz 2008). The current and expected climate change impacts on SOD-infected forests will likely increase the vulnerability of coastal redwood and mixed conifer-hardwood ecosystems (Frankel et al. 2008).

In the Midwest and eastern U.S., the invasive emerald ash borer (EAB) is creating landscape-level change and impacting the cultural practices of indigenous peoples who use black ash (*Fraxinus nigra*). The EAB (*Agrilus planipennis* Fairmaire) is an invasive beetle from Asia that has caused widespread ash (*Fraxinus* spp.) mortality. Despite aggressive eradication efforts, EAB, first discovered in Michigan in 2002, has spread to 18 states and two Canadian provinces (Kovacs et al. 2010).[1] EAB dispersal occurs when adult beetles fly to a new host tree or, more significantly, when people unknowingly transport infested trees, logs, or firewood. EAB is projected to spread across much of the natural range of ash in the Northeast by 2019 (Kovacs et al. 2010). The economic impact of EAB-related street tree removal and replacement in a 25-state region is estimated at $10.7 billion—a cost that does not include community amenity values associated with the loss of landscape trees, losses to forest landowners and the forest products sector and falling stumpage values as markets respond to a glut of dead trees (Kovacs et al. 2010).

The black ash, one of three ash species in addition to green (*Fraxinus pennsylvanica*) and white ash (*Fraxinus americana*) in Maine, is a highly important "cultural keystone species" (Garibaldi and Turner 2004) for the Wabanaki peoples (*"people of the dawnland"*) of Maine and the Maritimes. The ecological idea of a "keystone" species has been thought of, variably, as a species that "holds the system in check," or "whose impact on its community or ecosystem is large," or that "performs roles not performed by other species or processes" (Garibaldi and Turner 2004). Cultural keystone species play a similar role in the functioning and resilience of culture. Something is deemed a cultural keystone species by: the intensity

[1] Cooperative Emerald Ash Borer Project—USDA-APHIS Map: http://www.emeraldashborer.info/files/MultiState_EABpos.pdf

and multiplicity of use, naming and terminology in a language, role in narratives or ceremonies, persistence and memory of use, level of unique position in culture, and the extent to which it provides opportunities for resource acquisition beyond the territory (Garibaldi and Turner 2004).

For the Wabanaki nations of Maine (the Penobscot Indian Nation, Passamaquoddy Tribe-Pleasant Point, Passamaquoddy Tribe-Indian Township, Aroostook Band of Micmacs, and the Houlton Band of Maliseet Indians), the black ash serves critical roles in the social, cultural and economic spheres of contemporary life. The impact of invasive species on, as well as indigenous peoples' efforts to protect, cultural keystone species, is an important issue largely ignored in the literature on invasive species (Pfeiffer and Voeks 2008). The cultural impacts of invasive species is especially important in light of climate change, which will bring other stressors to ecosystem services that will also greatly impact tribal cultures (Kofinas et al. 2010).

The cultural importance of black ash is reflected in Wabanaki origin stories, wherein Gluskabe, the Wabanaki trickster hero, shot an arrow into the basket tree (the black ash), giving rise to the people who came into the world singing and dancing. Given this context, there is no substitute for the ash in Wabanaki culture. Moreover, baskets made of black ash are the oldest art form in New England and represent an original "green," value-added, sustainable forest product. The loss of ash and the associated basketry tradition would have deep economic, cultural and spiritual effects on tribes. Sales of ash basketry exceed $150,000 each year and many tribal household incomes are partially dependent upon this resource (Daigle and Putnam 2009). More than 95 % of tribal basketmakers in Maine live on or near reservations—many at or below the poverty level. Indigenous basketmakers and ash harvesters are working collaboratively with university researchers, state and federal foresters, landowners, and others to prevent, detect, and respond to the invasive EAB (Ranco et al. 2012).

3 Tribal adaptation in response to forest changes and wildfire threats

3.1 Tribal engagement in Landscape Conservation Cooperatives

Tribes are working with diverse partners to develop climate adaptation strategies. Amongst these partners are Landscape Conservation Cooperatives (LCCs), collaborative networks designed to coordinate conservation science and better address local and regional concerns related to conservation problems.

The North Pacific Landscape Conservation Cooperative (NPLCC) has collected tribal input for adaptation to identify and prioritize tribal responses to climate change. The NPLCC's Science and TEK sub-committee, with input from American Indians, Alaska Natives, and Canadian First Nations, has identified "effects of change in air temperature and precipitation on forests" (Jenni et al. 2012) as a priority, acknowledging fire as a secondary mechanism in response to climate.

The Upper Midwest and Great Lakes LCC has supported research to identify climate-vulnerable terrestrial species and natural communities, such as white-tailed deer and boreal and hardwood forests. Transitions in precipitation and temperatures threaten forest resources that tribes depend upon. Changes in the length of the spring fire season will likely increase stress or affect competition between different trees. In particular, a warmer climate could result in greater forest fires that degrade or reduce sugar maples (food) and black ash (basketry). Droughts coupled with extreme weather events could impact conifer germination and result in shifts in the range of tree species (Hoene 2010; Rose 2010). Changes in climate and fires would result in forest species compositions that tribal communities have not historically encountered. These broad geographic changes in forests directly affect wildlife, plants and other culturally significant resources.

3.2 Collaboration in tribal forest management

Many tribal and agency resource managers are using silvicultural treatments and fire to strategically mitigate the effects of climate change and wildfire (Rose 2010; Wotkyns 2010). Interagency-tribal partnerships are utilizing timber harvesting, hazardous fuels reduction, and prescribed burning as restorative treatments (Mason et al. 2012). In the U.S. Southwest, agencies, organizations, and Pueblo tribes are integrating restoration treatments to mitigate climate change and wildfire impacts (Bradley 2012; Wotkyns 2010).

Collaboration among groups with disparate perspectives but common goals are invaluable to increase investment and sense of ownership, enhance social capital and cooperation, and disrupt power dynamics that in the past have led to the exclusion of some groups—especially indigenous peoples (Bliss et al. 2001; Fernandez-Gimenez et al. 2008; Reo 2010; Wondolleck and Yaffee 2003). In the Northeast, work is underway to involve tribes in Emergency Response Planning efforts with invasive species such as the EAB. Collaborative efforts to address EAB as it approaches Maine have resulted in four areas of research and actions that are being employed: mapping ash resources, developing policy guidance, public education and stakeholder engagement, and seed collection (Ranco et al. 2012). Research is underway to quantify annual radial growth of black ash using dendrochronological techniques to identify trees best able to tolerate climatic variability and that possess the growth characteristics that make suitable Native American basket-trees. This effort will help characterize sites where black ash is ecologically important and be utilized to develop a quantitative model to identify areas likely to support high-quality basket-trees. The quantitative model may also be combined with U.S. Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) data to identify the occurrence and proportion of high-quality black ash stands that are at most risk for EAB infestation. A major outcome of this effort is to integrate spatial, scientific and indigenous knowledge to create statewide suitability maps for Maine's black ash, indicating sites associated with basket-quality trees and vigorous growth. Ultimately, this knowledge will be used to guide EAB monitoring, detection, and response activities that may contribute to collaboration for addressing future climate change and invasive species. Another goal is to provide regional responses to invasive species within the contours of indigenous resource management values (Pfeiffer and Voeks 2008). Figure 1 llustrates a map of the Cooperative Emerald Ash Borer Project.

A 2011 report evaluating the federal-tribal relationship under the Northwest Forest Plan found that improving consultation through Memorandums of Understanding (MOU) resulted in strengthened government-to-government relationships. In 2000, the Quileute Tribe developed an MOU with the Olympic National Forest acknowledging the Tribe's right to hunt, fish, and gather within the ceded lands outlined in the 1855 Treaty of Olympia. In 2008, the National Park Service (NPS) Olympic National Park and eight Olympic Peninsula tribes signed an MOU defining the trust responsibilities of the federal government, clarifying responsibilities and expectations of the NPS and the tribes, and establishing a framework for stronger government-to-government consultation (Harris 2011). MOUs demonstrate pathways to uphold the trust responsibility, while fostering productive partnerships between agencies and tribes.

The Tribal Forest Protection Act (TFPA) of 2004 offers another example of federal policy fostering federal-tribal partnerships in restoration and natural resource management. The TFPA authorizes the Secretaries of Agriculture and Interior to give consideration to tribally-

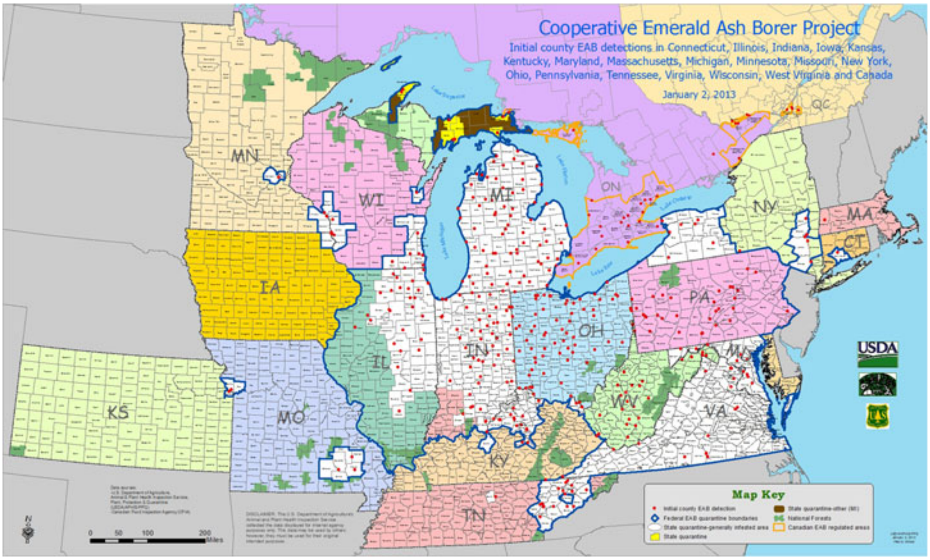

Fig. 1 The Emerald Ash Borer (EAB) beetle has destroyed tens of millions of ash trees in 18 states and continues to expand to other states. http://www.aphis.usda.gov/plant_health/plant_pest_info/emerald_ash_b/index.shtml

proposed stewardship contracting or other projects on Forest Service or Bureau of Land Management (BLM) lands bordering or adjacent to Indian trust land (PL 108–278, 2004). TFPA projects must protect tribal trust resources from fire, disease, or other threats coming off of Forest Service or BLM lands, and offer a mechanism for federal-tribal partnerships to address climate change on tribal lands.

4 Conclusion

Forest disruption and changes in species composition resulting from climate change could lead to the loss of culturally important resources, negatively impacting tribal subsistence, culture, and economy. To address these challenges, robust federal-tribal relationships are needed, particularly when changes affect treaty rights, tribal lands, and resources held in trust. Collaboration, knowledge-sharing, and joint action by tribes and nontribal stakeholders can lead to more effective and sustainable planning efforts around climate change and invasive species.

Climate change impacts on forests will not only affect tribal traditions and access to wildlife and plants; it will affect tribal sovereignty and the treaties, federal policies, and federal trust responsibilities that support tribal access to cultural resources (Whyte 2013). Treaties establish the basis for the Government-to-Government relationship between tribes and the United States government, which is grounded in the U.S. Constitution, and elaborated through statutes, federal case law, regulations and executive orders. The impacts of climate change on tribal sovereignty and indigenous peoples more broadly are described in greater detail elsewhere in this special issue (Whyte 2013; Hardison and Williams, submitted for this issue). Climate change impacts on tribally valued forest resources will require an understanding of how treaty and reserved rights may be affected. Strong Government-to-Government relationships will ensure help that tribes, state and federal agencies and other partners work together to sustain tribal access to culturally important forest resources and habitat.

Tribal involvement in agency resource management and climate change initiatives could include monitoring for species changes in forest habitats, using TEK to understand how culturally-important species may be shifting in composition or distribution, and developing adaptive strategies for fire and forest management. TEK is as much about what to look for, what questions to ask, and how to go about research in a collaborative manner, as it is an additional form of data. While non-indigenous researchers have played a major role in advancing our knowledge about climate change, this must "always [be] preceded by trust-building, development of working relationships, and respect for areas that should not be researched" (Berkes 2009:153). This requires scientists to become more accepting of other kinds of knowledge (Berkes 2009). Bringing together traditional Western science and TEK requires scientists and TEK practitioners to recognize that "indigenous knowledge systems seem to build holistic pictures of the environment by considering a large number of variables qualitatively, while science tends to concentrate on a small number of variables quantitatively" (Berkes 2009:154).

TEK and tribal involvement in climate research, assessments and policy formation can foster and inform strategies to address climate impacts to forests. The current gap in studies on the cultural impacts to tribes from climate change affects on forests requires meaningful tribal engagement in research and dedicated support to investigate these issues for tribes. Tribal engagement has made climate impacts on forests a priority for the NPLCC. And tribes have offered specific guidance to the NPLCC on the needs and potential priorities specific to tribes in managing ecosystems, habitats, species, and resources in light of current and projected climate change effects (Tillmann and Siemmann 2012). Tribal engagement in national climate initiatives such as the National Fish, Wildlife and Plants Climate Adaptation Strategy, Climate Science Centers and Landscape Conservation Cooperatives are critical to building an understanding of how tribes may be affected by climate change, and to inform tribally-appropriate climate strategies. The 2013 National Climate Assessment, a report on the impacts of climate change in the U.S. coordinated by the U.S. Global Change Research Program, provided tribes with such an opportunity through direct tribal input and the inclusion of a chapter on climate impacts to tribal communities, resources, and the value of TEK in identifying adaptation strategies. This will help inform the efforts of resource managers across the nation and provides an example of the type of engagement tribes should have in climate policy and programs.

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Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0745-0

Changing streamflow on Columbia basin tribal lands—climate change and salmon

Kyle Dittmer

Received: 12 November 2012 / Accepted: 17 February 2013 / Published online: 17 April 2013

Abstract Over the last 100 years, linear trends of tributary streamflow have changed on Columbia River Basin tribal reservations and historical lands ceded by tribes in treaties with the United States. Analysis of independent flow measures (Seasonal Flow Fraction, Center Timing, Spring Flow Onset, High Flow, Low Flow) using the Student *t* test and Mann-Kendall trend test suggests evidence for climate change trends for many of the 32 study basins. The trends exist despite interannual climate variability driven by the El Niño–Southern Oscillation and Pacific Decadal Oscillation. The average April—July flow volume declined by 16 %. The median runoff volume date has moved earlier by 5.8 days. The Spring Flow Onset date has shifted earlier by 5.7 days. The trend of the flow standard deviation (i.e., weather variability) increased 3 % to 11 %. The 100-year November floods increased 49 %. The mid-Columbia 7Q10 low flows have decreased by 5 % to 38 %. Continuation of these climatic and hydrological trends may seriously challenge the future of salmon, their critical habitats, and the tribal peoples who depend upon these resources for their traditional livelihood, subsistence, and ceremonial purposes.

1 Introduction

For 36 years, the Columbia River Inter-Tribal Fish Commission (CRITFC), along with its member tribes, the Nez Perce Tribe, the Confederated Tribes of the Umatilla Indian Reservation, the Yakama Nation, and the Confederated Tribes of Warm Springs Reservation of Oregon (Fig. 1), have worked to halt and reverse the decline of Pacific Northwest salmon, steelhead, Pacific lamprey, and sturgeon populations. These fish are of great cultural, subsistence, and commercial value to CRITFC's member tribes. Salmon are

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-013-0745-0) contains supplementary material, which is available to authorized users.

K. Dittmer (✉)
Columbia River Inter-Tribal Fish Commission, 729 NE Oregon Street – Suite 200, Portland, OR 97232-2107, USA
e-mail: ditk@critfc.org

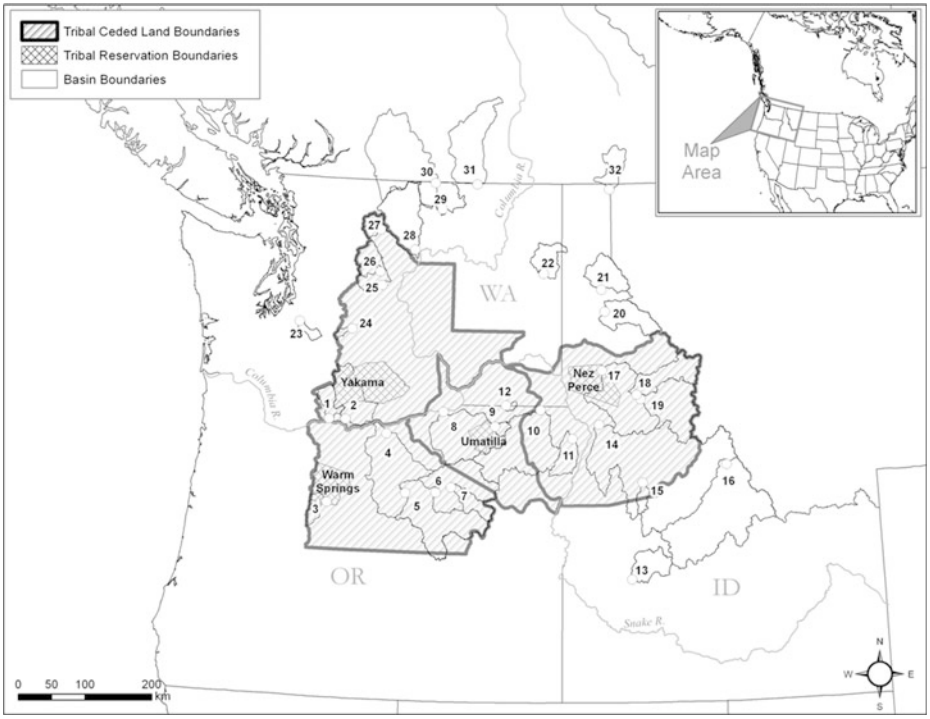

Fig. 1 Columbia River Treaty-Tribal lands and ceded areas (refer to Online Resource 1 for stations)

more than just a major food source—they are an important part of tribal longhouse religious services (e.g., First Salmon ceremony), cultural identity, sense of traditional place, traditional nutritional health, transferal of traditional values to the next generation, and livelihood (CRITFC 2013a). Salmon are the first in a line of sacred foods (Drummond and Steele 2013)—elk, deer, roots, and berries—that have been in decline due to degraded ecosystems (which are likely to be more vulnerable to future climate change impacts). CRITFC is a technical service agency for its member tribes, who, due to federal court interpretations of treaties with the United States (Weaver 1997), are co-managers of the fishery resource, along with the states of Oregon, Washington, and Idaho as well as NOAA-Fisheries and U.S Fish and Wildlife Service. CRITFC produced a comprehensive basin-wide salmon restoration plan, called Wy-Kan-Ush-Mi Wa-Kish-Wit or "Spirit of the Salmon" (CRITFC 1995), which includes recommendations for river flows, hydropower operations, and temperature regimes to increase fishery productivity. The plan is being updated, which will include strategies to mitigate for climate change, and will be available by July 2013.

CRITFC and its member tribes are concerned about climate change impacts to treaty-protected tribal fishery, water, and food resources. Climate change impacts could negatively affect critical life history stages for salmon and their habitat (ISAB 2007; Mantua et al. 2008; Crozier et al. 2008).

This study offers a retrospective analysis of changes in tributary streamflow that occurred during 1904–1930 to 2009 for the Columbia Basin tribal lands and ceded areas (i.e., territory ceded to the United States by the tribes in the Treaties of 1855 in exchange for the right to fish, hunt, and gather native plants on ancestral lands). This study serves as an important hydrological baseline for anadromous fish (e.g., salmon, Pacific lamprey, etc.) habitat and productivity that may be altered by climate change as a future limiting factor.

Salmon spend 50–90 % of their lives in the ocean (Quinn 2005). Their initial life cycle in the rivers and lakes is crucial for their survival chances in the estuary and coastal ocean. Salmon start as eggs laid down in river gravels during August-October (Fig. 2). The length of development depends on the Temperature Unit, the seasonal accumulation of heat energy. By spring, when the TU reaches 500, salmon fry hatch in the gravels where they stay and grow. By late spring and summer, when the TU reaches 1000, they are large enough as smolts to migrate downriver. The migration season is April through September (Fig. 3). Long-term changes to their freshwater habitats will likely impact their long-term survival and recovery prospects. For example, warming water temperatures can cause early emergence for fry (see Fig. 11, Mantua et al. 2008). Quinn (2005) noted that salmon have been highly challenged by human activities for over 100 years: "Given the high fishing rates, habitat loss and degradation, careless transfers of fish among basins, overzealous hatchery propagation, and other stressors, the remarkable thing is not that salmon are in danger but that they still persist at all...."

Pacific lampreys, a critical tribal cultural food resource, spend 60–70 % of their life-cycle in freshwater (Quinn 2005). Lampreys are often associated with Pacific Salmon as an indicator species and an important ecological component of freshwater streams providing marine-derived nutrients. The development of hydropower, degradation of habitat, and passage barriers have likely contributed in a decline from almost 380,000 adults counted at Bonneville Dam in 1969 to less than 30,000 in recent years (Luzier et al. 2011). The

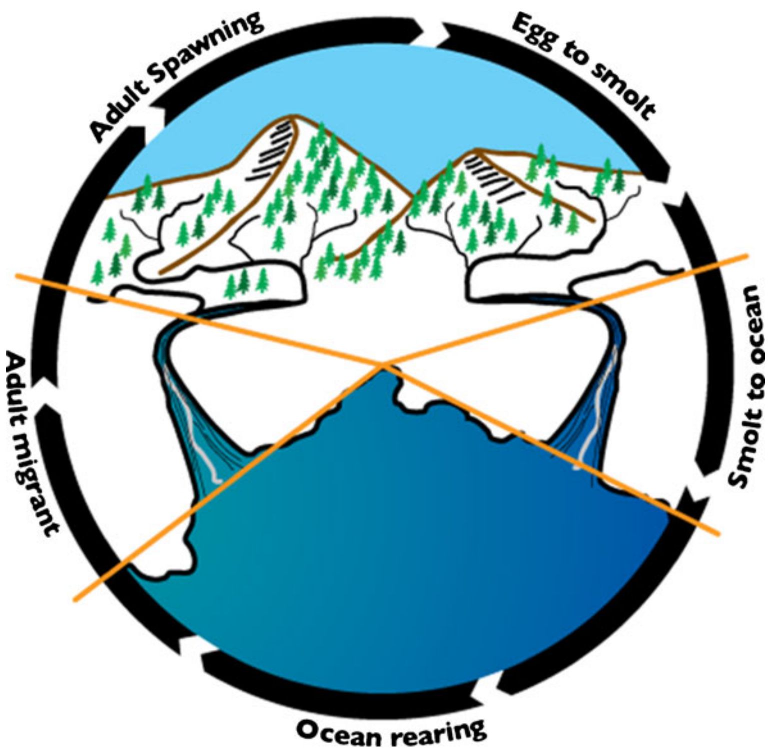

Fig. 2 Salmon Life Cycle (CRITFC 2013b)

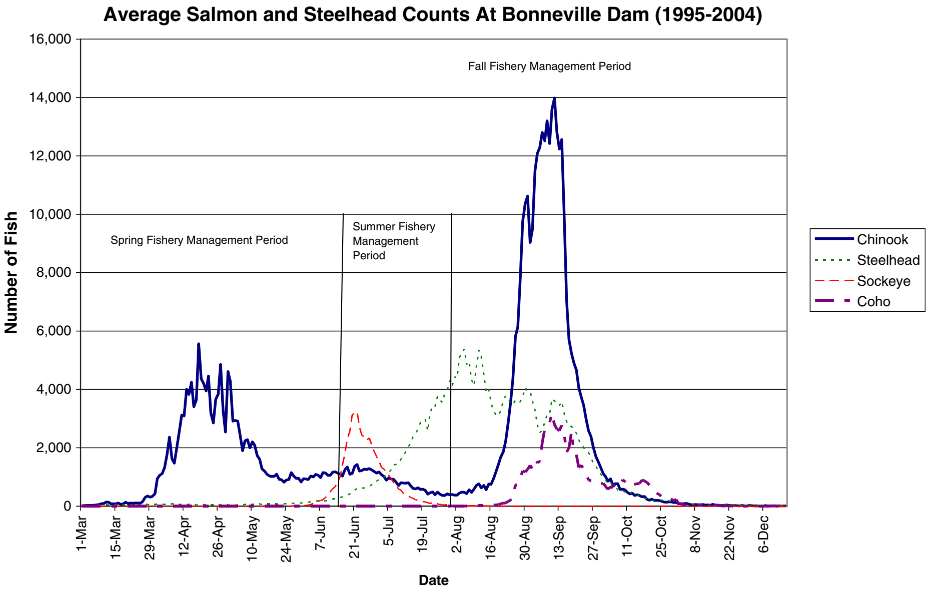

Fig. 3 Seasonal adult salmon abundance and run timing for the Columbia basin, which shows how biological timing intersects with changing streamflow (FPC 2012)

Columbia Basin tribes have developed a Lamprey Restoration Plan (CRITFC 2013c) to address these issues with the goal to restore lamprey throughout their entire range.

Changing tributary streamflow fueled by future climate change will be layered upon a Columbia-Snake River Basin (NPCC 2007) which is the most developed and regulated hydropower system in the world (Cohen et al. 2000). Anadromous fish must migrate through 1–9 major run-of-river projects on the Columbia and Snake Rivers (Fig. 4) twice in order to reach their spawning grounds in the tributary basins, once as juveniles heading to the ocean and later as adults migrating upstream to their spawning grounds. The development of 30 major dams for the Columbia River Basin Federal hydro-system, from 1938 (Bonneville Dam) to 1983 (Revelstoke Dam, BC), was for flood control, hydropower, then later on irrigation, navigation, and recreation. While upstream fish passage was originally accommodated at many dams, until recently, downstream passage and protection measures of critical habitat were not.

2 Methods

2.1 Temperature and precipitation data

Monthly values of the Geographic Information System-based PRISM or Parameter-evaluation Regressions on Independent Slopes Model (Daly et al. 1994; PRISM 2012) for 1900–2009 were processed for most basins in this study. The 800-m cell-resolution climate data were intersected by study basin delineations. Mean climate data were then computed for each study basin, except for those basins in Canada, as PRISM data doesn't extend into Canada. The PRISM method is ideally suited for complex mountainous terrain (PRISM 2012). Annual maximum and minimum air temperatures plus precipitation data were averaged as three-year moving averages for each basin to enhance the signal-to-noise pattern.

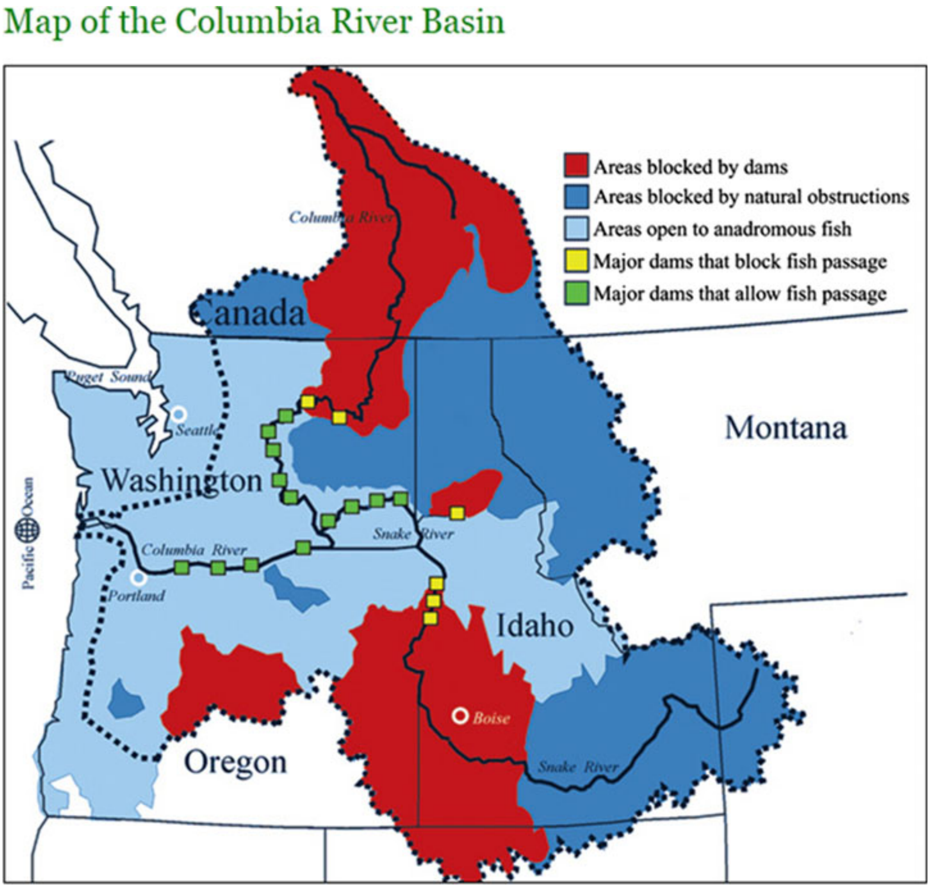

Fig. 4 Columbia River Basin (dotted line) and its salmon (i.e., anadromous fish) passage aspects (NPCC 2013)

2.2 Flow data

The flow data series were downloaded for U.S. Geological Survey (USGS) stream gages (USGS 2012) and imported into EXCEL spreadsheets. Many gages are part of the USGS Hydro-Climate Data Network or HCDN (Slack and Landwehr 1992). The HCDN gages are deemed desirable for climate change studies because they represent basins with few or no anthropogenic effects and are best suited for climate change studies.

The observed flow data for 21 of 32 basins in this study were “naturalized” by removing historical irrigation diversion (i.e., gravity and sprinkler systems) and return-flow depletion data compiled by the Federal power-marketing agency, BPA (BPA 2011). BPA obtained irrigation withdrawal monthly flow data from water reports from the USDA’s National Agricultural Statistics Service (USDA-NASS 1997), USGS National Water-Use Program (USGS 1995), and the British Columbia Census on Agriculture. The BPA analysis also took into account the changing (usually increasing) irrigation withdrawals over time. In EXCEL, the modified-adjusted flow dataset is the observed flow series minus the irrigation depletion data (negative values) for each day of each month throughout the station record. An example is the Methow River at Pateros, for May 1, 2000: 2961 cfs (natural)=2860 (observed)−[−101 (irrigation)].

2.3 Tributary basins

Thirty-two snowmelt-dominant basins located on or near tribal ceded lands, were selected (Fig. 1, Online Resource 1) with the criteria: (1) at least 65 years of streamflow record, (2) no more than 20 % record gaps, (3) unregulated streams, (4) avoid very low flow records with inconsistent trends (i.e., poor signal-to noise patterns) relative to adjacent basins. Some station records with gaps were filled in by daily synthetic flows derived by the author based on significant (R2=0.5–0.9) multi-month regressions with one or two adjacent basin daily gage records. Due to the significant influence of water resource projects and other anthropogenic changes, other gage records deemed desirable were rejected from this study.

The study basins are located in warm-summer continental climates (see Fig. 4 in Elsner et al. 2009). The majority of precipitation falls in autumn-winter followed by dry summers. The peak runoff occurs in May-June. The lowest flow occurs in August through October. Columbia Basin snowfall occurs November through March; snowmelt is during April through July (Mote and Salathé 2010).

2.4 Flow measures

This study considers independent ways to measure changes in streamflow and includes:

(1) Seasonal Flow Fraction (SFF). The SFF is defined as a ratio of the spring-summer streamflow volume to the water year streamflow volume (Stewart et al. 2005). Aguado et al. (1992) plus Dettinger and Cayan (1995) performed similar analysis for the basins of the Sierra Nevada Mountains. Dettinger and Cayan (1995) also noted that the hydroclimate of the Pacific Northwest varied more considerably than California. The spring-summer period is important to the life cycle of salmon (ISG 2000), as water is needed for juvenile and adult salmon habitat and migration, and so will be emphasized. For this work, the spring-summer streamflow is defined as flow rate during April through July, which corresponds to the same period in Stewart et al. (2005) for basins across the western U.S.

(2) Center (of volume) Timing (CT). The CT is the Julian-day of the median of the daily streamflow accumulation through the water year (Stewart et al. 2005). The CT is preferable to the observed daily peak flow, because unusual weather events (e.g., rain-on-snow) can obscure an annual peak flow (Hidalgo et al. 2009; Maurer et al. 2007). The CT is a close proxy to the annual peak flow and allows for more consistent, robust results.

(3) Spring Flow Onset (SFO). The SFO is the start-date of the annual snow-melt. Cayan et al. (2001) defined the start-date of the SFO when the cumulative total of daily flow departures from the mean streamflow are at a minimum. This is equivalent to the date when streamflow shifts to a rapid rise due to snow-melt. This study uses the period January 1 to July 31 to compute the mean, as most of the annual snow-melt in the Pacific Northwest is complete by July. Stewart et al. (2005) used January 9 to September 5. Cayan et al. (2001) used January 9 to July 27. Those studies examined stream gages across the western U.S., which encompasses more varied terrain than is considered in this study of the rivers of the Columbia Basin.

(4) High Flow (HF). The HF is defined as the largest daily streamflow that occurs during one autumn month. October, November, and December were chosen, given the seasonal increase in Pacific Coast storms and high flow timing shifts across the western U.S. (Hamlet and Lettenmaier 2007), the vulnerable time for salmon egg nests (ISAB 2007), and the linkage between egg mortality and high flow scour events (Jager et al.

1997). A frequency analysis was plotted for each basin. The 10-year and 100-year flows were computed from these data using the log-Pearson Type III and Gumbel distributions (Linsley et al. 1982).

(5) Low Flow (LF). The LF is defined as the 7Q10 flow (i.e., lowest streamflow over seven consecutive days having a 10-year recurrence interval) during August 1 to November 15, when most anadromous fish are likely to spawn and need critical habitat, e.g., flows of adequate quantity and quality with cool temperatures. Jager et al. (1997) state that salmon egg mortality risk is caused by extreme temperatures, loss of habitat due to extreme high and low flow events, and superimposition of eggs. A frequency analysis was plotted for each basin. The 7Q10 was computed using the log-Pearson Type III and Gumbel distributions (Linsley et al. 1982).

2.5 Trend analysis and hydroclimatology

Linear trends of the five streamflow metrics were computed for annual, three-year and five-year moving average time steps. Each trend was compared during the following time periods: 1962–2009 vs. 1900–61, 1977–2009 vs. 1925–56, 1947–76 vs. 1900–24, 1999–2009 vs. 1900–24, and 1977–98 vs. 1925–46. Each time period represents a part of the Pacific Ocean climate variability, as measured by El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Both strongly control Columbia Basin hydrometeorology and its influence on Columbia Basin runoff (Miles et al. 2000; Mote and Salathé 2010). Time periods are based on natural breaks of the PDO, which Mantua et al. (1997) identified as 1900–24 (cold phase), 1925–46 (warm phase), 1947–76 (cold phase), and 1977–98 (warm phase), and chosen to minimize the climate variability influence of the PDO.

The two-tailed Student *t* test (i.e., comparing the means and distributions of two populations) and the Mann-Kendall trend test were computed for each flow measure for each basin. The Mann-Kendall test (Helsel and Hirsch 1992) is a non-parametric statistic that detects a trend in time-series data, which can be very scattered. These tests are commonly used in water resources analyses (Helsel and Hirsch 1992). Onoz and Bayazit (2003) showed that the *t* test and Mann-Kendall test are good tests for trend detection using streamflow data from Turkey.

3 Results

3.1 Temperature and precipitation data

The PRISM data (Online Resource 2) show a mean change of +0.6 °C (range −0.2 to 1.7) and +1.6 °C (range 0.4 to 2.4) per century, for the maximum and minimum air temperatures, respectively, and +46 mm (range −14 to +210) per century for precipitation. The Mann-Kendall results show significance ($p \leq 0.05$ level) in trends for 18 basins of maximum air temperature, 32 basins for minimum air temperature, and four basins for precipitation. The R2 values of 0.1–0.75 are driven by variable interannual weather patterns of the Pacific Northwest (Hamlet et al. 2005).

3.2 Seasonal flow fraction

The 3-year moving average SFF (Online Resource 3), on average, declined 16 % per century for spring-summer flows (range of −35 % to −2 %). Of the 32 basins none experienced an increase in SFF for spring-summer flows, nine basins had a 2–10 % decline, eleven had an

11–20 % decline, ten had a 21–30 % decline, and two had a 32–35 % decline. A multi-year moving average can enhance the signal-to-noise aspect and statistical robustness of the annual data. The 3-year moving average gave the best results (vs. annual or 5-year steps). The 3-year SFF average is 1 % higher than the annual data. Plots of annual data (Online Resource 3) do show the temporal changes and trend of variability. The basins of northeast Oregon, using non-HCDN data, compare very well with adjacent basins that use HCDN data.

The *t* test shows the significance ($p \leq 0.05$) in the SFF flows for the Late Century (1962–2009) versus the Early Century (1900–61) period (i.e., "LC vs. EC"), representing a mixed PDO phase (i.e., part warm, part cold phase) of two lengthy time periods (3-year moving average data) for 16 basins (Online Resource 4). A hybrid period (i.e., start of a warm phase PDO continuing through part of a cold phase), 1977–2009 (representing modern conditions) vs. 1925–57 (i.e., "W-C" or warm-cold phase), has significance for 17 basins. Other time spans of PDO phases were not as robust. The average standard deviation (Online Resource 4) increased 5 % (range −18 % to +57 %) with 15 basins showing a positive trend and implies that hydrometeorological variability is increasing. The Mann-Kendall results show significance ($p \leq 0.05$) for a trend for ten (SFF), two (CT), and four (SFO) basins.

3.3 Center timing

The 3-year moving average CT seasonal date (Online Resource 5) has decreased (i.e., shifted earlier) on average by 5.8 days (range −17.2 to +2.3 days). The 3-year CT average is +0.6 day higher than the annual data. Plots of annual data are shown in Online Resource 5. The *t* test shows the significance ($p \leq 0.05$) in the mean flows (3-year moving average data) for the "LC vs. EC" period and hybrid warm-cold ("W-C") phase PDO for six basins. The average standard deviation increased 3 % (range −16 % to +89 %) with 12 basins showing a positive trend (Online Resource 4) and suggests that hydrometeorological variability is increasing. There is a preponderance of smaller shifts in CT for the higher elevation basins above 1,200 m (Online Resource 5) but the scatter of the data makes more refined interpretation difficult.

3.4 Spring flow onset

The 3-year moving average SFO seasonal date (Online Resource 6) has shifted earlier on average by 5.7 days (range to −32.7 to +11 days). The 3-year SFO average is +0.8 day higher than the annual data. Plots of annual data are shown in Online Resource 6. The *t* test shows the significance ($p \leq 0.05$) in the mean flows (3-year average data) for the "LC vs. EC" period for five basins. The hybrid warm-cold phase PDO has significance for six basins. The average standard deviation increased 11 % (range −24 % to +57 %) with 21 basins showing a positive trend (Online Resource 4), which implies hydrometeorological variability is increasing. The SFO and CT data are significantly correlated for 44 % (annual) and 58 % (3-year average) of the gages. Stewart et al. (2005) found a 74 % correlation for SFO and CT.

3.5 High flows

Online Resource 7 shows for the "LC vs. EC" period the average 100-year flood decreased 7 % (range −72 % to +113 %) in October, increased 49 % (range −24 % to +150 %) in November, and increased 4 % (range −38 % to +38 %) in December. The *t* test shows the significance ($p \leq 0.05$) in the flows for the "LC vs. EC" period for three basins (October) and one basin (November). Given the highly complex pattern of change across basin geography, elevation, location, and autumn month, a break-out of these months (Online Resource 7) gives more statistical robustness rather than looking at a bulk seasonal value. Plots of annual data (Online Resource 7) show the likelihood for higher flow has increased since 1961. The average standard deviation (Online Resource 4) decreased 5 % in October (range −76 % to +142 %), increased 61 % in November (range −5 % to +194 %), and increased 21 % in December (range −29 % to +176 %), which suggests that the variability in mid-autumn rainfall-driven flood events is increasing. Hamlet and Lettenmaier (2007) have studied the change in flood risk in the western U.S. for snow and rain-dominated basins and detected an increasing flood risk in basins with a transient (i.e., mixed snow/rain) hydrology.

The HF results are consistent with Dettinger (2011) which describes Atmospheric River (AR) events, a.k.a. "Pineapple Express" storms (i.e., intense warm, moist jet-streams from near Hawaii) striking California and the impact of climate change. He noted an increase of AR events and flooding in the last 50 years and to expect an increase in future frequency and magnitude (+0.3 to +7.2 AR days per century).

3.6 Low flows

Online Resource 8 shows that for the "LC vs. EC" period the average 7Q10 increased 4 % (range −38 % to +38 %). The average standard deviation (Online Resource 4) increased 1 % (range −65 % to +71 %) with 16 basins showing a positive trend. The *t* test shows significance ($p \leq 0.05$) for six basins. The Mann-Kendall results show significance ($p \leq 0.05$) for a trend for seven basins. An increase in frequency of low flows exists for the basins of northeast Oregon and central Idaho and a 5 % to 38 % decrease (i.e., drying trend) of the east-slope Washington Cascades and north Idaho. Time series plots (Online Resource 8) show the trend for select east-slope Washington Cascades basins.

3.7 Basin elevation analysis

GIS was used to delineate basins into areas (Online Resource 9) above and below 1,200 m, the modern mean midwinter snow-lines for the Cascade Mountains (Meyer and Dodge 1988), and 1,800 m, which Mote (2003) identified as an elevation above which there is little change in the trend of the historical April 1st snow water equivalents for the Cascades. Local NWS meteorologists report that midwinter snowlines hover at 1,200 m for basins west of the Cascades and 300–600 m east of the Cascades.

For land below these two elevation criteria, the effects of long-term trends are great, as seen in the CT data (Online Resource 5). The mean basin area below 1,200 m is 41 % (range 0 % to 98 %) and below 1,800 m the mean is 80 % (range 7 % to 100 %). The greatest streamflow change occurs in the low elevation transition-type basins of northeast Oregon (which is near the main salmon migration corridor) and north-central Idaho.

4 Discussion

4.1 Trends in streamflow timing

For their 302 stations across western U.S., Stewart et al. (2005) saw 0–20 % declines in the SFF for the Pacific Northwest stations for their 1948–2002 record. This shift compares well with the 2–35 % declines in this study. For the CT metric, Stewart et al. (2005) found that 10–30 day earlier shifts were clustered in the Pacific Northwest, Sierra Nevada, coastal Canada, and Alaska and compares well with the +2 to −17 day shifts in this study. For the SFO metric, Stewart et al. (2005) saw 10–30 day earlier shifts in timing using the SFO metric and compares well with the +11 to −32 day shifts in this study.

These shifts are likely driven by changes in warming winter temperatures, which affects the Snow Water Equivalent (SWE) of snowpacks (Mote et al. 2008). Plots (Online Resource 10) of peak April 1st SWE versus the November-March precipitation of SNOTEL/snow courses (Barnett et al. 2005) in/near the study basins show the trend of SWE as −0.2 % to −0.9 % per year, as a fraction of total winter precipitation. This finding is supported by Pelto's (2008) −0.4 % to −1.1 % per year (1946–1005) decline in the April 1st SWE for five SNOTEL sites in the North Cascades of Washington.

4.2 Pacific Ocean and Pacific Northwest hydroclimatology

The interannual variability of Pacific Northwest weather patterns caused by the positive and negative annual phases of ENSO, combined with the 20–30 year phases of PDO (Fig. 3 from CIG 2012), is a confounding reality when trying to interpret streamflow trends. Other workers have also noted this obstacle. Beebee and Manga (2004) warn that the starting point of a trend analysis, which depends on a PDO phase, determines the type of trend, if any. They used USGS records before 1940 for small unregulated and undeveloped basins in Oregon to increase the ratio of snowmelt signal to Southern Oscillation Index and PDO indices. Their results suggest that the strength of the correlation depends on the PDO phase, but the correlation coefficients are only 0.10-0.57. It may not be possible to delineate a strong trend of climate elements, given such interannual variability, with 100 years of data.

4.3 Fishery restoration

The change in streamflow timing and volume will have differing impacts on Columbia Basin salmon, depending on the species, which determines their residence time in the river (Fig. 3). The 16 % decline per century in spring-summer flow suggests that less habitat may be available for salmon and other fish, as salmon fry emerge from their gravels in early spring, begin rearing, then migrate to the ocean. Possible impacts may include earlier (than historical norms) out-migration to the ocean for spring Chinook, changed timing of available freshwater and/or marine food sources, reduced summer flow, and longer returning migration times, impacting fall Chinook, steelhead, and coho the most, as they migrate during summer. Summer flows are expected to decline further. Trying to assess shifts in flow timing and salmon migration is problematic. For outmigrating juvenile sockeye (FPC 2012) during 1985–2009 (longest period available) at Rock Island Dam the CT for fish increased 5-days per decade while the CT for the Okanogan River (where 85 % of the Columbia sockeye originate) decreased 2.5-days per decade. Migrating fish are impacted by flow, temperature, and turbidity, so confounding factors makes it difficult to assess specific impacts.

The increase of the 100-year October/November/December floods suggests that some major rain and rain-on-snow events could give duel positive and negative outcomes. A positive aspect is that mountain floods can be the catalyst for many hydrologic and physical processes that can enhance watershed ecosystem health such as cleaning silt out of spawning gravels and move nutrients downstream, which would benefit salmon (Swanson et al. 1998). A negative outcome is that very high runoff can scour the streambed and disrupt or destroy redds (i.e., egg nests), which fall Chinook, coho, and steelhead construct in September and October. Their eggs are most susceptible to strong increases in autumn flood risk.

Summer flows are also a concern. The 7Q10 analysis suggests a mixed-picture. The basins near the east-slope Washington Cascades and north Idaho had the highest negative change (i.e., lower flows), which is consistent with future trends noted in Elsner et al. (2009). The basins of northeast Oregon and central Idaho had an increase in summer flow. Lower summer flows decrease the amount of spawning habitat, can produce higher water temperatures, and reduce dilution of pollutants. Higher water temperatures have negative impacts on returning adult salmon reproduction, physiological response (e.g., heat shock, stress, disease resistance, bioenergetics and feeding), and pre-spawning mortality (McCullough et al. 2009). Pelto (2011) noted a substantial increase in the number of very low flow days in the glacier/snowmelt dominated Skykomish River Basin. Many Washington Cascade basins are fed by summer glacial melt, which is in decline due to warming temperatures (Grah and Beaulieu 2013).

CIG (2009) used the IPCC A1B and B emissions scenarios to show that Washington snowmelt basins could become transient and transient basins could become rainfall-dominant by 2020, 2040, and 2080. The CIG study also shows an increase in the 20-year winter flood events, especially for basins in the central and southern Washington Cascades and a 5 %–40 % reduction in the summer (7Q10) flows by 2080. Mantua et al. (2010) shows the sensitivity of Washington State salmon freshwater habitats to climate change impacts. Increase in AR storms (Dettinger 2011) could pose even further risk to salmon eggs during their vulnerable incubation time.

Battin et al. (2007) focused on the Snohomish River basin (western Washington Cascades, north of Seattle, transient hydrography), using the GFDL R30 A2 and HadCM3 A2 scenarios for 2025 and 2050. Their conclusions are similar to the CIG study. Battin et al. (2007) and Crozier et al. (2008) noted that salmon mortality will likely increase due to higher water temperatures, lower flow for salmon spawners, and higher winter peak flows which may disrupt salmon nests. Chinook stocks could decline 20 % by 2050 (Battin et al. 2007).

The impact of future climate change on the Columbia Basin tribal lands, water resources, and cultural resources (such as native plants) will likely be profound. Some of these basins are near the transition point for snow and rain, 0 °C, as illustrated by Graves (2009). Graves noted that basins located closer to the Pacific Ocean and at moderate elevation, such as the Deschutes Basin in central Oregon, are most vulnerable, and high elevation basins, such as the Salmon Basin in Idaho, are more likely to be less affected by climate change impacts than lower elevation basins. Graves produced future scenarios with a snowpack model, using the IPCC A2 and B1 data, for 1971–2000, 2010–39, 2040–69, and 2070–99 for select tribal basins: Oregon – Deschutes, John Day, Umatilla; Washington – Yakima, Klickitat; Idaho – Salmon, Clearwater. It appears that some of these basins would change from snowmelt dominant to transient during the 2040s to 2080s. Such a shift would mean earlier snowmelt, lower summer flow and warmer late spring and summer water temperatures for such basins. Water temperature work continues on vulnerable basins, such as the Grande Ronde in northeast Oregon (Graves 2012).

Since 1938, the development and regulation of the Columbia River Basin hydro-system has shifted the annual lower Columbia River peak flow to earlier in the season and has been substantially reduced, primarily for flood control protection. Hydropower operations have increased winter flows (with less water for spring-summer) and irrigation has reduced summer flows (Online Resource 11), increasing fish travel times during spring-summer, which may reduce in-river survival, and reducing critical habitat, both contributing to the loss of fish productivity (ISG 2000). The development of the hydro-system, combined with overharvest from over 100 years ago (Online Resource 12) and the destruction of river habitat are stressors that have forced a steep decline of salmon abundance (ISG 2000). The reduction in summer flows can enhance the problems due to climate change and higher winter flows can increase impacts from more frequent winter flood events due to climate change noted in the headwaters.

5 Conclusions

Results of five independent flow measures indicate trending evidence for climate change for many of the study basins, despite strong interannual hydro-climate variability. The greatest change occurs in the low elevation basins of northeast Oregon, north Washington Cascades, and north-central Idaho. The trends imply that juvenile salmon may be forced to outmigrate earlier with less tributary river water, returning adults may be challenged by lower and warmer summer flows, and more scouring winter streamflows threaten their redds. Continuation of these trends may have negative impacts on Columbia Basin anadromous fish, their freshwater habitats, and the tribal peoples dependent upon them for spiritual and cultural sustenance.

Due to observed and projected changes, CRITFC and its member tribes are working on mitigation/adaptation projects (Gephart 2009, CRITFC 2013d). The Nez Perce implemented a Carbon Sequestration Plan on the Nez Perce Forest (NAU 2013). They also developed a Clearwater River Adaptation Plan that uses a forestry-watershed-economics approach (NPT 2011). Umatilla staff are conducting a project analyzing plant distribution changes due to climate change, which would impact their First Foods. Yakama staff are collaborating with USGS on a project to interview elders on climate change impacts. Warm Springs staff are negotiating with John Day River landowners to form conservation easements to reconnect the river to its tributaries and floodplains. Reconnections are an important climate change strategy to mitigate for increases in summer stream temperature, higher flows in winter, and lower flows during summer. Finally, there are legal and policy tools that tribes can consider when planning climate change strategies (UC-NRLC 2007).

Acknowledgments This work was partially supported by a 2009 EPA Indian Environmental General Assistance Program Grant (#GA97020802-02) and a 2009 NOAA-PCSRF Watershed-Climate Change Grant awarded to CRITFC. Thank You to David Graves for the PRISM data and making the maps for Fig. 1, S1, S5, S10, S14, S15, S16, S20, S24; internal review by CRITFC's Bob Heinith, David Graves, Laura Gephart, and Brian McIlraith; Dr. David Garen, USDA-Natural Resources Conservation Service; Jim Ruff and John Fazio, Northwest Power and Conservation Council; Julie Maldonado and Benedict J. Colombi plus the reviewers. Your effort is appreciated and improved the paper.

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DOI 10.1007/978-3-319-05266-3_11
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0799-z

Exploring effects of climate change on Northern Plains American Indian health

John T. Doyle · Margaret Hiza Redsteer · Margaret J. Eggers

Received: 27 January 2013 / Accepted: 18 May 2013 / Published online: 22 June 2013

Abstract American Indians have unique vulnerabilities to the impacts of climate change because of the links among ecosystems, cultural practices, and public health, but also as a result of limited resources available to address infrastructure needs. On the Crow Reservation in south-central Montana, a Northern Plains American Indian Reservation, there are community concerns about the consequences of climate change impacts for community health and local ecosystems. Observations made by Tribal Elders about decreasing annual snowfall and milder winter temperatures over the 20th century initiated an investigation of local climate and hydrologic data by the Tribal College. The resulting analysis of meteorological data confirmed the decline in annual

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-013-0799-z) contains supplementary material, which is available to authorized users.

J. T. Doyle (✉)
Crow Water Quality Project, Little Big Horn College, 8645 S. Weaver Drive, Crow Agency, MT, USA
e-mail: johndoyle91@gmail.com

J. T. Doyle
Apsaalooke Water and Wastewater Authority, Crow Agency, MT, USA

J. T. Doyle
Crow Environmental Health Steering Committee, Crow Agency, MT, USA

J. T. Doyle · M. H. Redsteer
Crow Tribal member, Crow Reservation, MT, USA

M. H. Redsteer
US Geological Survey Flagstaff Science Campus, Flagstaff, AZ, USA
e-mail: mhiza@usgs.gov

M. J. Eggers
Little Big Horn College, 8645 S. Weaver Drive, Crow Agency, MT 59022, USA
e-mail: eggersm@lbhc.edu

M. J. Eggers
Microbiology Department/CBE, Montana State University Bozeman, PO Box 173980, Bozeman, MT, USA

snowfall and an increase in frost free days. In addition, the data show a shift in precipitation from winter to early spring. The number of days exceeding 90 ˚F (32 ˚C) has doubled in the past century. Streamflow data show a long-term trend of declining discharge. Elders noted that the changes are affecting fish distribution within local streams and plant species which provide subsistence foods. Concerns about warmer summer temperatures also include heat exposure during outdoor ceremonies that involve days of fasting without food or water. Additional community concerns about the effects of climate change include increasing flood frequency and fire severity, as well as declining water quality. The authors call for local research to understand and document current effects and project future impacts as a basis for planning adaptive strategies.

1 Introduction

Climate change impacts present distinct risks to human health throughout Indian country. Although documented in Alaska (Brubaker et al. 2011a) and the Southwest (Redsteer et al. 2013a, b; Redsteer et al. 2010), these issues are not as well researched for Northern Plains Tribal communities. To address this data gap, observations of Crow Tribal elders in addition to changes in monitored temperature, precipitation and streamflow in the Little Bighorn River valley, Montana are provided. Located in south central Montana, the Crow Reservation encompasses 2.3 million acres, including three mountain ranges and three large river valleys. Approximately 8,000 of the 11,000+ Tribal members reside on the Reservation, primarily along the rivers and creeks. The majority of communities, including the "capital" town of Crow Agency, are situated in the Little Bighorn River valley (Fig. 1). The Crow language is still widely spoken and many cultural traditions continue to be practiced today. Water is one of the most important natural resources to the Crow community and has always

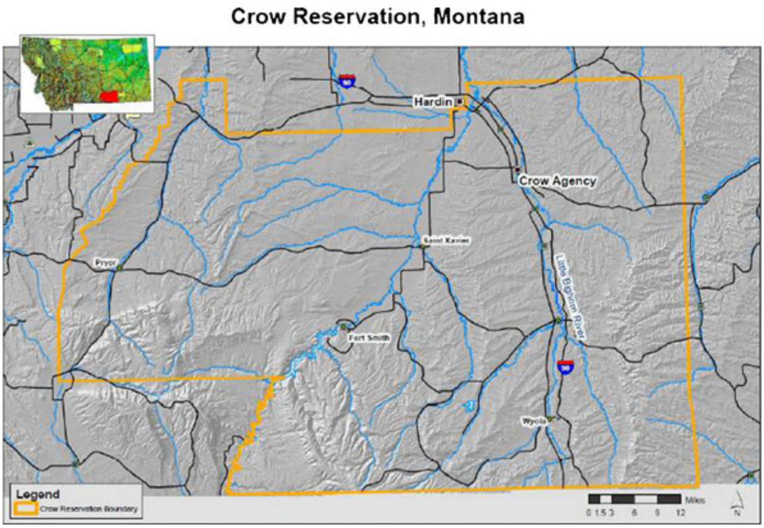

Fig. 1 Map delineating Crow Reservation (in *yellow*) and proximity to Hardin, MT where meteorological data for the study was collected, 15 miles northwest of Crow Agency, MT. The Reservation is southeast of Billings, MT, with the Reservation's southern border on the Montana-Wyoming State boundary. (Map prepared by Eggers; inset courtesy US Department of Agriculture 2013)

been held in high respect among Tribal members. River and spring waters are still used in many ceremonies (Knows His Gun McCormick et al. 2012).

The observations of local climate changes are those made by first author John Doyle, a Tribal Elder, and reflect experiences he and his peers have had over a span of many years. Additionally, other Elders shared their observations with Doyle for this article,[1] or contributed to discussions at meetings of the Crow Environmental Health Steering Committee (Cummins et al. 2010a, b). To compare and integrate the changes observed by the community with existing monitoring data, analyses were conducted of the local National Weather Service records as well as the US Geological Survey discharge data for the Little Bighorn River. Local knowledge and these physical measurements were in agreement, and provided complementary insights. This process has triggered further community discussions about potential impacts on water quality, forest and rangeland resources, subsistence foods and public health. Challenges facing these communities are broad in scope and demonstrate the need for vulnerability assessments and planning to reduce current and future climate-related health impacts.

2 Crow elder observations

Community Elders have observed long-term changes in the local climate, including declining winter snowfall, milder winters and warmer summers. Elders from all Districts of the Reservation remember that the ground used to be covered in deep snow and stayed frozen from November to March—while today the prairies are bare grass for much of the winter (S Young, J Doyle, personal communication, 2007; D Small, MA LaForge, K Red Star, D Yarlott, UJ Bear Don't Walk, personal communications, 2013). Sometimes the snow was so deep that it was a real struggle to feed cattle (D Small, personal communication, 2013). Children could ice skate throughout the winter; now winter days are often above freezing (S Young, personal communication, 2012). Even Tribal members in their thirties note that winters are not as cold as when they were children (W Red Star, V Buffalo, personal communications, 2013). Every spring, massive ice jams on the Little Bighorn River used to break up and scour out the river bottom and banks; today the ice is thin by early spring and what remains melts quietly away (J Doyle, personal communication, 2012). A locally important mountain spring, visited repeatedly over the years, has been steadily moving downslope, causing concern that the water table has been dropping due to reduced snowfall (J Doyle, personal communication, 2013).

Elders note that climate changes are affecting subsistence food plants, especially berries. (See also Lynn et al. 2013). Many species of berries have long been gathered as staple foods, including juneberries, chokecherries, elderberries and buffalo berries. Now these shrubs and trees sometimes bud out sufficiently early in the spring that they are vulnerable to subsequent cold snaps that kill the blossoms, so they never fruit. In years that shrubs bear fruit, the timing has changed: chokecherries used to ripen after the juneberries, and now they ripen at the same time (V Buffalo, personal communication, 2013). Elderberries in the mountains now ripen in July instead of in August (J Doyle, personal communication, 2013). Buffalo berries were traditionally harvested after the first frost, as freezing sweetened the berries. Now buffalo berries are dried out before the first frost hits, so are no longer worth gathering (L Medicine Horse, personal communication, 2013). Additionally, some trees now come out of dormancy during mid-winter warm spells, and die when the temperature drops below freezing again. Similar trends in the phenology of lilacs and honeysuckle have been

[1] The eight named Tribal Elders and two younger Tribal members who provided comments specifically for this article all agreed to the use of their names.

observed by the Western Regional Phenological Network: spring bloom dates in the 1980s–1990s were 5 to 10 days earlier than they were in the 1960s–1970s. This shift is attributed to warming spring temperatures in western North America by 2° to 5 °F (1°–3 °C) during the period of observation (Cayan et al. 2001).

Ceremonial practices are being affected by high temperatures. In May and June, sundances are held; these are three- or four-day outdoor events during which the participants fast, dance and pray. One older sundance chief, who for decades has led this ceremony near Crow Agency every Father's Day weekend, notes that the June weather has gotten progressively hotter and therefore the sundance has become increasingly difficult for fasting participants. He remarked that the cattails, which community members bring to participants for relief from the heat, used to average 6 ft in length, and are now only about 3 ft long (L Medicine Horse, personal communication, 2013). Cattail (*Typha latifolia*) vigor, including both root and shoot biomass, has been found to decline with increasing soil dryness (Asamoah and Bork 2010). Other traditional sundancers have concurred that dancing has become tougher with progressively hotter summer weather (L Kindness and anonymous Crow Environmental Health Steering Committee member, personal communications, 2013).

The river ecosystems appear to be warming in parallel with surface temperatures, as has been documented both nationally and globally (NCADAC 2013). Reduced stream flows and warmer summers, in addition to increased agricultural non-point source pollution, is affecting the Little Bighorn River. Apparent impacts to fish and other aquatic species include changes in brown trout location, a species that prefers cooler waters. Although these trout used to be found at the tributary mouth of the Little Bighorn River, near Hardin, they are now more than 35 miles upstream (A Birdinground, personal communication, 2010). Recently, bass have been observed in the lower Little Bighorn River, where they never lived before. Catfish with skin lesions have been caught. Freshwater mussel and frog populations have declined. These observations, along with knowledge of river contamination, have caused some families to give up subsistence fishing (J Doyle, personal communication, 2010). Others note declining fish populations, and believe the changes in climate are a contributing factor (V Buffalo, personal communication, 2013).

3 Confirmation of Elders' observations of recent climate change using monitoring data

The Elders' observations discussed in the previous section were compared to climate and hydrologic data available for the Crow Reservation and vicinity, as well as published regional climate trend information. While observational data are perhaps more subjective and less quantitative than monitored precipitation and streamflow, they have the potential to contribute greatly to understanding what ecosystem changes may be occurring as a result of multiple stressors, including climate change. They also provide information in regions where data are limited. The Reservation is part of the ancestral homelands of the Crow people, and so existing relationships with and uses of plants, game and water resources go back many generations. Parallel observations by Elders from all the Districts of the Reservation, such as of declining snowfall, provide multiple data points and are invaluable in the absence of SnoTel sites on the Reservation. Their observations are also particularly relevant to daily life, illuminating for instance how climate change is impacting food supply, cultural activities and human health.

Climate and hydrologic analyses were focused on the Little Bighorn River valley of the Crow Reservation, which includes the majority of the Reservation's population. Stream flow records for the Little Bighorn River were used because it flows north through the entire Reservation, passing through Crow Agency, before joining the Bighorn River at Hardin (Fig. 1). Weather station data were selected based on station history, completeness and appropriateness of records that would elucidate local changes to the Little Bighorn River valley near Crow Agency, Montana.

Hardin and Crow Agency weather station data were combined in this evaluation in order to provide a more complete history of changes that have occurred over the longest period of time (National Climate Data Center 2013). These data were supplemented by information on trends in precipitation and temperature from Montana's Climate Division 5 (MT CD5), which covers south-central Montana, including all of the Crow Reservation as well as counties to the west and north (Supplement Documents I and II). Other available weather data relevant to the Crow Reservation are limited. There are no other weather stations within the Little Bighorn River valley with sufficiently complete data to be worth analyzing, nor in nearby river valleys within 75 km of Crow Agency, Montana (Supplement Table I). Crow Agency data collection began operation in 1897, has reasonably complete data and is in a small rural community that has had no urban growth (0 %). However, the Crow Agency weather station was discontinued more than 20 years ago, limiting the usefulness of its data for an analysis of recent changes. Hardin, located 15 miles northwest of Crow Agency, began collecting data in 1909. Although the early record is missing much of the 1920s and 1930s, it has a nearly complete record of precipitation, temperature and snowfall from July 1948 to today (March 2013). The town of Hardin has had a negligible urban growth rate (2 %) over the past 75 years, hence urban growth is highly unlikely to have had a substantial impact on the weather data. The site is in an agricultural valley in the NOAA's Climate Division 5, south-central Montana. This weather station is 2905' (881 m) above sea level, and is located on the alluvial plain of the Bighorn River (Fig. 1).

Seasonal temperature variations in the Little Bighorn River valley are extreme, consisting of bitterly cold winters and very hot summers. These variations are reflected in the station data that show temperatures vary from −40 °F (−40 °C) in January and February, to above 100 °F (38 °C) in July and August, with an annual mean of 48.3 °F (9.1 °C). The number of days per year exceeding marked temperature thresholds has increased substantially from 1897 to 2012 (Fig. 2). The number of days per year exceeding 100 °F is highly variable. The

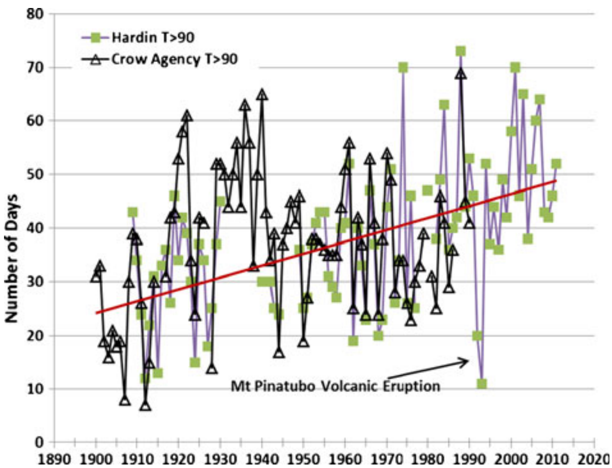

Fig. 2 Number of days per year with temperature exceeding 90 ˚F (32 ˚C) has doubled in the past century in Hardin and Crow Agency, MT. Data from National Weather Service daily records (National Climate Data Center). The *red line* indicates a linear trend of increasing high temperatures based on the data. (A dip in temperature in the early 1990s corresponds to a cold period produced by the volcanic ash from eruption of Mt Pinatubo.)

decadal-average number of days per year exceeding 100 °F has doubled from 1900–1909 to 2000–2009 (Supplement Table II). The increase in high temperatures recorded does not coincide with any changes made to weather station operation, but is consistent with trends in increasing temperatures for Montana Climate Division 5 (CD5) (National Climate Data Center). Montana CD5 data show average monthly temperatures over the past 110+ years have been steadily warming for the summer months of June through September, by 0.1° to 0.2 °F per decade (Supplement Document I). The warming trend observed in monitoring data supports the accounts and observations of the Crow Tribal sundancers.

Additional warming trends in winter temperatures are readily apparent in the number of frost-free days (days exceeding 32 °F), which has increased by about 7.2 days per decade (Fig. 3). In the 1950s there were on average 178 frost-free days per year, whereas since 2000 there have been 213 such days. The number of frost-free days per year has important implications for ecosystems because cold winters are responsible for killing off pests, such as bark beetles (Evangelista et al. 2011). As warm season weather extends in length, pests can have more than one reproductive cycle, further increasing their numbers.

This increase in number of frost-free days is consistent with Montana CD5 data showing that over the past 110+ years, average temperatures for the months of January through March have been steadily increasing (by 0.2 °F, 0.4 °F and 0.5 °F per decade respectively) (Supplement Document I). Elders' accounts that they used to be able to ice skate all winter long as children, and that the river ice was once much thicker in wintertime is consistent with these trends in cold temperatures observed in monitoring data.

Overall, Hardin's average temperature has increased from a mean of 45.6 °F in the 1950s to 50.1 °F since 2000. Average temperatures from the Crow Agency weather station records are nearly identical to the Hardin data for the years that collection occurred at both sites (Supplement Figure I).

These increases in average annual temperature and in the number of hot summer days and frost-free winter days, demonstrates that the climate changes projected by the draft National Climate Assessment (NCA) for the Northern Great Plains are already underway (National Climate Assessment and Development Advisory Committee (NCADAC) 2013).

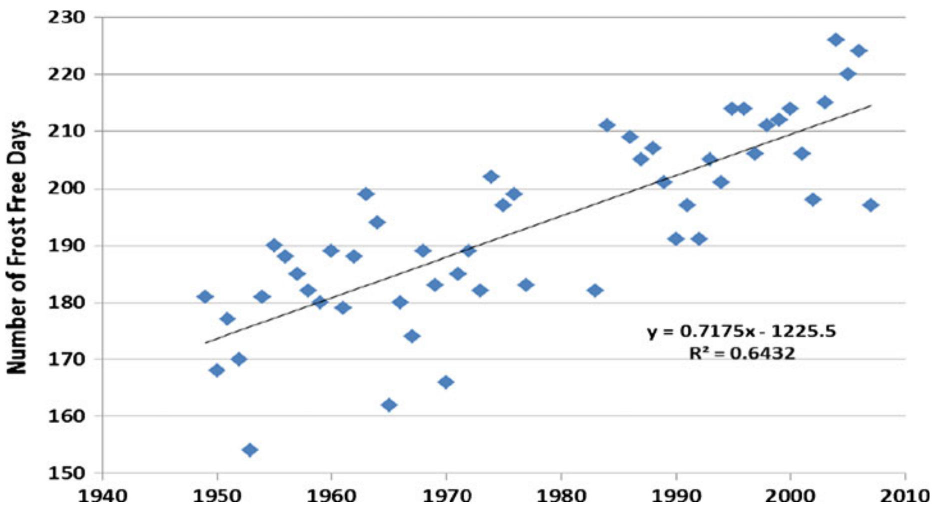

Fig. 3 Number of frost free days per year in Hardin, MT, calculated from historic daily observations. (Data source: National Climate Data Center.)

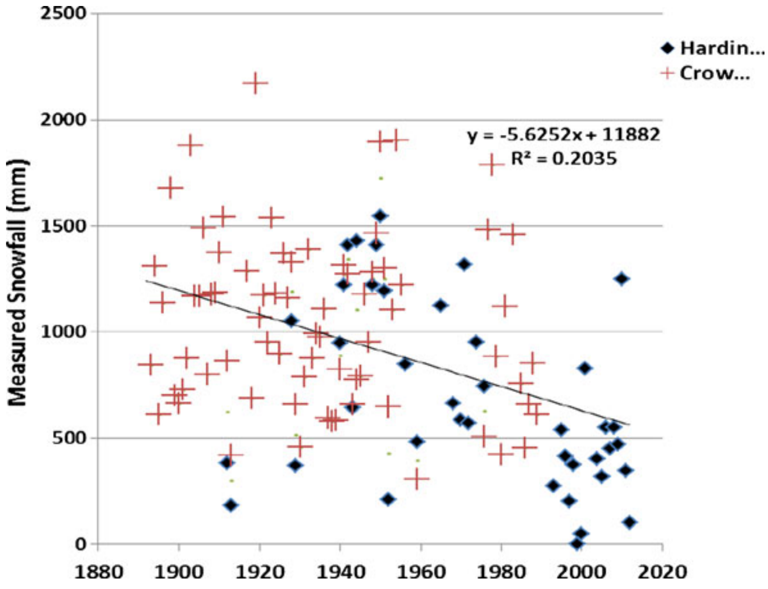

Fig. 4 Plot showing annual snowfall in millimeters from Hardin MT (1912–2012) and Crow Agency MT (1895–1990) observation sites, calculated in water years. The trendline is calculated from the average of measurements when both locations had measurements, and on the single site's measurements when only one station was operating. Years with more than 1 month of missing data were deleted from data plot, except for the earliest records. (Data source: National Climate Data Center.)

As temperatures warm, snowfall is likely to decrease because atmospheric temperatures are warm enough for precipitation to fall in a liquid rather than frozen state for a longer period during the year. Snowfall has decreased significantly in the region surrounding Hardin (Fig. 4). A similar trend in reduced snowpack has been documented for the Northern Great Plains in general, and for other parts of the western U.S. over the past half century (NCADAC 2013). For Montana CD5, including the Crow Reservation, winter precipitation (December through March) has been declining on average 0.05" per decade since 1895 (Supplement Document II). This regional trend has serious implications for local ecosystems, local temperature trends, recharge of aquifers and summer runoff in local streams and river systems, and hence also for Crow Agency, whose municipal water source is the Little Bighorn River. Snow covers the surface with highly reflective water crystals that help keep the surface cool by reflecting the sun's heat back into the atmosphere. Snow melts slowly, and as a result, the moisture delivered as snow infiltrates the substrate more effectively than rain. Also, mountain snowpack melts slowly during spring and summer, reducing the likelihood of flooding and providing riparian areas and communities with a constant fresh water supply during the hot summer months when water is needed most. The decline in winter snow pack is not being made up during other seasons; average annual precipitation in MT CD5 has been declining by 0.11 per decade (Supplement Document II).

The Elders' observations of decreased annual snowfall is confirmed by the research of Stewart et al. (2005) that showed a trend towards an earlier onset of the spring runoff peak throughout western North America. In addition, the Elders' observations were confirmed by an analysis of streamflow data for the Little Bighorn River. The USGS gaging station 06289000 on the Little Bighorn River at State line near Wyola, Montana, measures discharge from a drainage area of 193 square miles in the Big Horn Mountains. The station is located where the river leaves the Big

Horn Mountains and enters the valley floor, documenting flow before any significant withdrawals for agriculture or municipal uses. The river is a critical water source because it provides the municipal water source for Crow Agency and because the majority of the Tribe's population lives in the river valley. A US Geological Survey study of the Valley's groundwater resources found that the water in the Quaternary alluvium had a median total dissolved solids (TDS) concentration of 1,450 mg/L, while the median TDS concentration in the Judith River Formation was 1,000 mg/L (Tuck 2003). The EPA Secondary Standard for TDS is 500 mg/L, hence these levels are considered objectionable for municipal drinking water (EPA 2013). Neither aquifer provides a viable alternative water supply for Crow Agency's municipal use.

To reduce the "noise" from interannual variability in the spring runoff hydrographs, decadal averages of discharge for each day during May and June were calculated for the available data for the Little Bighorn River gaging station (06289000). The 1980s and 2000s had the earliest spring runoff peak of all decades on record (Supplement Figure II) (USGS 2012).

Decadal averages of monthly mean daily discharge from 1940 to 2009 were similarly calculated. Plotting these data show that the 1980s and 2000s had not only the earliest but also the lowest spring runoff of all decades on record (Fig. 5). If this pattern continues, it would be in agreement with research documenting the effects of warmer temperatures on decreased streamflow (Pederson et al. 2010; McCabe and Clark 2005).

Recent devastating spring floods of the town of Crow Agency in 2007 and 2011 warrant examination of flood history to see if their frequency is increasing. The data show that the mean daily discharge for May 2007 was more than 100 cfs higher than any other May on record for the previous 70 years of streamflow data (Supplement Figure III). The USGS data document the well-remembered "epic" June 1978 flood, when the nearest gauging station on the Little Big Horn River (close to Hardin), set an all-time record of 11.78 ft, which was 3.78 ft above flood stage. The devastating 2011 flood, in which more than 200 homes were damaged, set a new gauging station record of 12.32 ft (Olp 2011; Thackeray 2011) (Supplement Figure IV). Local oral history tells of a similarly major flood in the 1920s (Doyle, personal communication, 2012, citing Alice Yarlott Other Medicine). Note that high mean daily discharge of the Little Bighorn

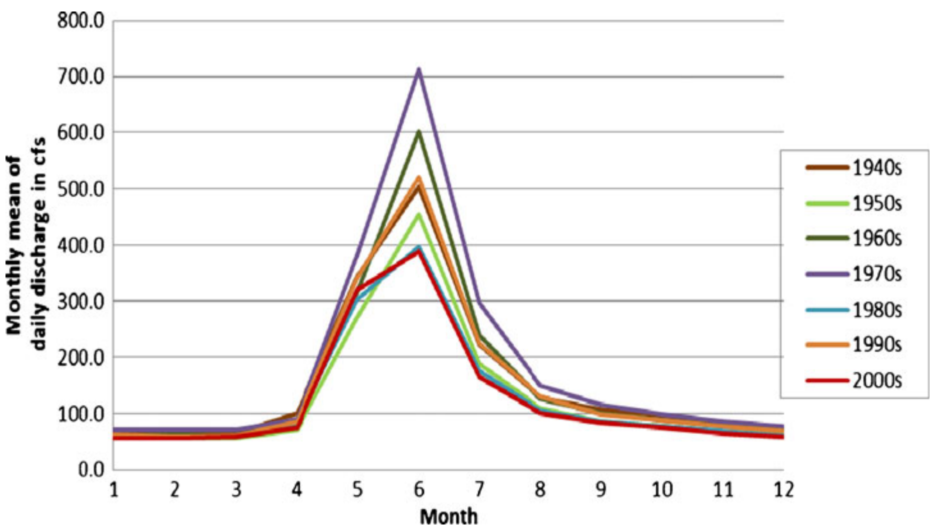

Fig. 5 Monthly averages of daily mean discharge by decade for Little Bighorn River at State Line near Wyola, Montana (station 06289000). (Data source: USGS 2012)

River at State Line near Wyola, Montana (at station 06289000) for the month of June has not always resulted in flooding of Crow Agency. Over the past century, the town of Crow Agency has experienced severe floods about every 40 to 50 years, but the unusual early season flood in May 2007, followed closely by a more damaging flood in 2011, has raised community concerns about increased flood frequency and severity. Trends in CD5 data show a shift in precipitation from winter months to the spring (increasing in April). These trends may also contribute to the probability of spring floods.

The physical data sets available, the descriptions of climate and ecosystem change by Elders, and recent flooding and fire events on the Reservation are almost all in accordance with descriptions of current and predicted climate impacts described in the draft National Climate Assessment (NCA) in the chapters on the Great Plains, Native Lands and Resources, and Water Resources (NCADAC 2013). The additional information contributed by Crow Tribal Elders provides a better understanding of climate impacts and phenological changes experienced by the community, compared to what can only be cautiously surmised from the monitored climate and stream discharge data. These local data are an essential complement to regional predictions, especially when evaluating local ecosystem change and vulnerable communities (e.g. Patz and Olson 2006). The draft NCA's prediction of increased annual precipitation for the Northern Great Plains is contradicted by both the local mountain stream discharge data and the MT CD5 data. The MT CD5 data document an absolute long-term regional decline in annual precipitation for south-central Montana.

4 Anticipated vulnerabilities for the Crow community and local ecosystems

The Apsaalooke [Crow] Water and Wastewater Authority ("the Authority"), which works with the Reservation communities of Crow Agency, Wyola and Pryor on their municipal water and wastewater systems, is particularly concerned about the effects of the apparently declining streamflow, increased agricultural demand and more frequent spring flooding on drinking water availability, water quality and community health. As the Little Bighorn River is the source water for the municipal water treatment plant supplying Crow Agency and the regional Indian Health Service Hospital, and low flows in August already strain the ability of the plant to obtain sufficient water to supply the town, further decreases in streamflow from reduced snowfall could be challenging. The monthly averages of daily mean discharge for the months of June and July were the lowest on record for the 2000s and 1980s (Fig. 5). The demand from agriculture for water for irrigation is already increasing (J. Doyle, personal communication, 2012). Clearly, running out of municipal drinking water for the town and the hospital would have deleterious health impacts.

Research conducted by Little Big Horn College (LBHC) and the Crow Environmental Health Steering Committee, with partners from Montana State University Bozeman and the University of New England, has already found substantial microbial contamination of local rivers during spring and summer months. For instance, *E. coli* levels in the Little Bighorn River exceeded 1,200 colony forming units (CFU)/100 mL during spring 2007 (Ford et al. 2012); surface waters with an *E. coli* geometric mean exceeding 126 CFU/100 mL are considered unsafe for swimming (EPA 2012). Testing initiated by the Crow Agency Water Treatment plant, and conducted at an EPA-certified lab, showed that the *E. coli* concentration in their Little Bighorn River source water exceeded 7,100 CFU/100 mL during spring runoff in 2009 (Bright Wings 2009, cited in Connolly et al. 2010). The documented *E. coli* concentrations mean that under the EPA's Long-Term 2 Enhanced Surface Water Treatment Rule, the Treatment Plant falls into "Bin 4," the highest risk category for *Cryptosporidium* in the source water. *Cryptosporidium* is a protozoan pathogen, which in its oocyst form can survive in the environment for months, and is highly resistant to chlorination (US EPA 2001). The infective dose for humans is low, and an infection can be fatal for immune-compromised individuals (US EPA 2001). *Cryptosporidium* has contaminated public water systems elsewhere in the US, especially after heavy precipitation coinciding with spring snow melt (Patz and Olson 2006). Hence, the Crow Agency Water Treatment Plant is required to meet additional treatment requirements for *Cryptosporidium* removal by October 1, 2014 (Connolly et al. 2010). The Tribe's limited operations and maintenance budget for water treatment strongly constrains technology choices. More frequent spring flooding will only exacerbate these municipal water treatment challenges.

Spring flooding incurs multiple health risks to community members. During the 1978 flood, the sewer clogged and sewage backed up into homes (Thackeray 2011). In 2011, the flood washed wastewater from the Lodge Grass lagoon into the Little Bighorn River, which in turn inundated downstream homes and businesses. Twenty-two homes were destroyed and over 200 were damaged (Olp 2011). There was an increase in complaints about water damage to homes leading to mold infestation (M Eggers, personal communication, 2011). Molds release irritants and allergens, and can cause asthma attacks in some asthmatics (EPA 2010). Many people's wells were flooded; the Tribe's Environmental Protection Department subsequently shock chlorinated many of these wells but could not reach everyone affected. The Federal Emergency Management Administration's Montana Disaster Declaration designated the Crow Reservation as eligible for both Individual Assistance and Public Assistance (FEMA 2011). Experiencing two severe floods within 5 years, there is community concern about the impacts of continued increased flood frequency and severity, possibly driven by climate change.

The Authority, the Crow Tribe, Little Big Horn College and the local Indian Health Service hospital, working together as the Crow Environmental Health Steering Committee, with the support of academic partner Montana State University Bozeman, are working on several mitigation strategies to reduce waterborne microbial health risks (Cummins et al. 2010a, b; Eggers et al. 2012). First, a low cost, high tech home water filtration system was pilot tested for home use. This system is proving to successfully treat river water for microbial contamination such as *E. coli* for only pennies a day, so it can be safely consumed. The filters could provide an option for safer ceremonial consumption of river water, for families who found this culturally acceptable. Second, EPA funding is being sought to work with local ranchers to reduce non-point source pollution from livestock manure. Third, there are collaborations with other researchers to better elucidate the health risks from microbial contamination of river water, especially *Cryptosporidium* and *E. coli*. Finally, there are community education events and partnerships with educators to expand water quality education in the schools.

Warmer summer temperatures are also affecting the Crow Agency municipal water supply's distribution system, with implications for community health. During summer 2012, the soils in Crow Agency became so dry and hard that soil surface impact more readily shattered the older, underground concrete-asbestos drinking water lines. Until breaks are detected and repaired, water lines are vulnerable to contamination, creating health risks for water consumers. This also wastes precious water and increases infrastructure maintenance costs for an already financially strained system. The Water Authority has successfully raised funds to upgrade the distribution system and is replacing these old, fragile water lines.

The effects of decreased snowfall and warmer temperatures on forest health, wildfire severity and hence also human health are another community concern. As mentioned above, drier and warmer weather improve conditions for forest pests such as bark beetles, resulting in more dead timber and greater fire risk (Voggesser et al. 2013). Across the state of Montana, more than 1.2 million acres burned in 2012 (NOAA 2012)—the most acreage burned in recorded history, except for 1910 (Thackeray 2012).

The 2012 Sarpy Creek, Bad Horse, Plum Creek fires and more on the Crow Reservation resulted in the worst fire season in memory for the community. The fires were even worse on the adjoining Northern Cheyenne Reservation, where more than 60 % of their 445,000 acre Reservation burned. Homes and livestock were lost; the town of Lame Deer was evacuated; some areas were burned so badly the soil blistered, creating concern that the pastures and wildlife forage would not recover. If so, ranching and subsistence deer and elk hunting, vital to local families, could be impacted. There were days when the smoke was thick and heavy, but there are no measurements of air quality, so people concerned about the health risks had no way to assess the danger (J. Doyle, personal communication, 2013). This coming spring (2013), erosion is expected to become an issue for both soil and water quality. The full extent of the impacts of the 2012 fire season on land, water and human health are still unfolding.

5 Conclusion

Meteorological data from Hardin and Crow Agency, the USGS streamflow-gauging station on the Little Bighorn River and MT CD5 exhibit trends predicted and observed to be the result of the Earth's average warming by 0.7 °C this last century due to the greenhouse effect, with one exception: annual precipitation and apparently streamflow are declining, in contradiction to the prediction for increased precipitation in the Northern Great Plains (NCADAC 2013). Observations from Tribal Elders and the small amount of meteorological data available are in agreement. In addition, Elder observations suggest that the data trends are representative of the Little Bighorn River valley. Further investigation of these trends is needed to provide an account of when changes to ecosystems began, the magnitude of ecosystem changes that could be occurring, and any underlying mechanisms and stressors that may contribute to observed changes to plant and animal species.

The ecological effects of less snowfall, warmer temperatures, recently reduced streamflow, increasing flood frequency and fire severity are already being experienced by Crow Tribal members and other residents of Big Horn County. Additional research to understand and document the full extent of the consequent human health impacts has yet to be conducted. A "Climate Change Health Assessment," to include the steps of "scoping… surveying… analysis… and planning," as was conducted in northwest Alaskan villages (Brubaker et al. 2011b) would be invaluable. Such an assessment would be essential for the Crow Reservation community to plan for mitigation of the impacts on water and subsistence food resources, forest health, agriculture, ranching and community health. Other Northern Plains communities are encouraged to examine their local climate data and consider and plan for current and future impacts of climate change on their local ecosystems, water resources and public health.

While changes in climate and health impacts have been researched and documented for Alaskan Native and Southwestern Tribal communities, much less has been published about impacts on Tribes in the Northern Great Plains (NCADAC 2013). Recent publications documenting how climate change is affecting snowmelt hydrology and streamflow timing in the northern Rocky Mountains (Pederson et al. 2010; Hamlet et al. 2001), as well as the draft National Climate Assessment (NCA) (NCADAC 2013), suggest that Crow Reservation climate changes and concerns might be relevant to other communities in the region. Additionally, as local changes in climate shown in the NOAA record are not completely in agreement with the changes projected for the Northern Great Plains by the draft NCA (NCADAC 2013), there is a need for analyses at both local and regional scales. The addition of local data to regional projections is resulting in more engaged community discussions and will provide a better basis for community policy development and long range planning (Brubaker et al. 2011b). Therefore, this article describes how the local weather and discharge data has been analyzed, and the potential public health impacts, as an example that could be useful for other communities.

Acknowledgments Thank you to the many Crow Tribal members who contributed their personal observations of changes to the Reservation's climate, water resources and phenology over the recent decades, and particularly to Sara Young, whose initial observations inspired this work. Anne Camper (Montana State University Bozeman), David Anning (Arizona Water Science Center, US Geological Survey) and anonymous reviewers provided useful suggestions.

The work at Little Big Horn College was supported by a NSF Course, Curriculum and Laboratory Improvement grant; Center for Native Health Partnerships' Grant #P20MD002317 from NIH's National Institute of Minority Health and Health Disparities; EPA STAR Research Assistance Agreement #FP91674401 and an EPA - National Center for Environmental Research Grant # R833706. The content is solely the authors' responsibility; it has not been formally reviewed by the funders and does not necessarily represent the official views of the NIH or the EPA. The EPA does not endorse any of the products mentioned.

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DOI 10.1007/978-3-319-05266-3_12
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0747-y

The effect of climate change on glacier ablation and baseflow support in the Nooksack River basin and implications on Pacific salmonid species protection and recovery

Oliver Grah · Jezra Beaulieu

Received: 19 November 2012 / Accepted: 17 February 2013 / Published online: 5 April 2013

Abstract The Nooksack Indian Tribe (Tribe) inhabits the area around Deming, Washington, in the northwest corner of the state. The Tribe is dependent on various species of Pacific salmonids that inhabit the Nooksack River for ceremonial, commercial, and subsistence purposes. Of particular importance to the Tribe are spring Chinook salmon. Since European arrival, the numbers of fish that return to spawn have greatly diminished because of substantial loss of habitat primarily due to human-caused alteration of the watershed. Although direct counts are not available, it is estimated that native salmonid runs are less than 8 % of the runs in the late 1800's. In addition, climate change has caused and will continue to cause an increase in winter flows, earlier snowmelt, decrease in summer baseflows, and an increase in water temperatures that exceed the tolerance levels, and in some cases lethal levels, of several Pacific salmonid species. The headwaters of the Nooksack River originate from glaciers on Mount Baker that have experienced significant changes over the last century due to climate change. Melt from the glaciers is a major source of runoff during the low-flow critical summer season, and climate change will have a direct effect on the magnitude and timing of stream flow in the Nooksack River. Understanding these changes is necessary to protect the Pacific salmonid species from the harmful effects of climate change. All nine salmonid species that inhabit the Nooksack River will be adversely affected by reduced summer flows and increased temperatures. The most important task ahead is the planning for, and implementation of, habitat restoration prior to climate change becoming more threatening to the survival of these important fish species. The Tribe has been collaboratively working with government agencies and scientists on the effects of climate change on the

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

O. Grah (✉) · J. Beaulieu
Nooksack Natural Resources Department, Nooksack Indian Tribe, P.O. Box 157, Deming, WA 98244, USA
e-mail: ojgrah@gmail.com

hydrology of the Nooksack River. The extinction of salmonids from the Nooksack River is unacceptable to the Tribe since it is dependent on these species and the Tribe is place-based and cannot relocate to areas where salmon will survive.

1 Introduction

Glaciers in the North Cascades Mountains of Washington State are a critical water supply source, serving as water storage reservoirs, and their response to climate change will impact the region's water resources and fish habitat over the next century and beyond. The North Cascades occur in the north central and western portion of the State of Washington and are a very likely place for the occurrence of glaciers because of the high amount of winter precipitation (~80 % of annual mean) and relatively high altitude terrain that occurs in the snow accumulation zone (Hamlet et al. 2005). More than 700 glaciers cover 225 km^2 and yield approximately 800 m^3 of runoff each summer on the average (Post et al. 1971; Riedel and Larrabee 2011).

Air temperature, alpine snowpack, glacier extent, and streamflow in Washington have already experienced significant changes since 1950. Glacier area and volume loss have been extensive throughout the 20th century, and have been well documented by many researchers (e.g. Granshaw and Fountain 2006; Nolin et al. 2010; Riedel and Larrabee 2011; and Pelto 2010). The timing and magnitude of streamflow in a high relief, snow-dominated basin, such as the Nooksack River basin, is strongly influenced by changes in temperature and precipitation (Elsner et al. 2010; Bach 2002). The Nooksack River (Fig. 1) is comprised of three forks (North, Middle, and South) that converge near Deming, Washington, and is fed by glaciers on Mount Baker, Mount Shuksan, and other nearby peaks of the North Cascades. There are at least eight source glaciers within the Nooksack River watershed on Mt. Baker and include the Deming, Thunder, Coleman, Roosevelt, Mazama, Sholes, Heliotrope and Hadley glaciers (Fig. 1). If glacial recession continues at its present rate, many of these glaciers may disappear entirely and their contribution to streamflow could be lost (Bach 2002).

Forecasts developed from regional general circulation models (GCM) predict increases in temperature and variable changes in precipitation over the next century that will affect snow accumulation, snow melt, glacier size, and streamflow. Of particular concern in the Nooksack River is the substantial loss of glacier-melt contribution to streamflow during the low-flow summer season. Summer baseflows have already decreased and stream temperatures have increased thereby adversely impacting Pacific salmonid habitat and fish survival (Elsner et al. 2010; Mantua et al. 2010). Several of the nine salmonid species and populations (i.e., evolutionarily significant units, or ESU's) are protected under the federal Endangered Species Act (ESA). Of particular importance to the Tribe is spring Chinook salmon that return to hold, spawn, and rear in the Nooksack River. These fish are vital resources to the Tribe for ceremonial, subsistence, and commercial uses. Understanding the importance and magnitude of climate change effects on glacier-generated streamflow and fish habitat is imperative to effective planning for the restoration of damaged habitat under the current climate conditions and the future recovery and protection of fish in the Nooksack River watershed under future climate conditions. Since European arrival, the numbers of fish that return to spawn have greatly diminished because of substantial loss of habitat primarily due to human-caused alteration of the watershed. Although direct counts are not available, it is estimated that native salmonid runs are between 2 and 8 % of the runs in the late 1800's (Lackey 2000). Declines in salmon and habitat due to the

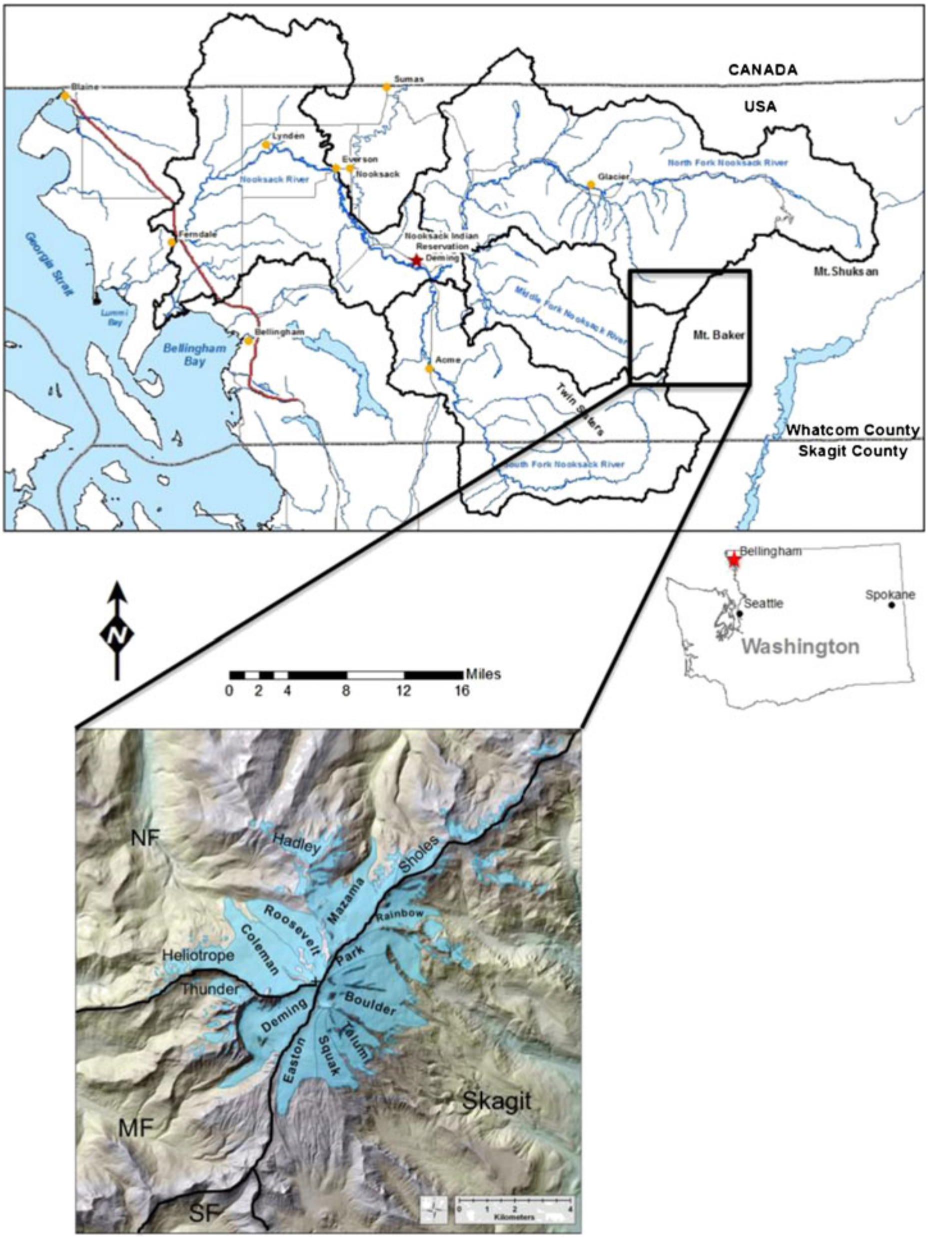

Fig. 1 Geography of the Nooksack River basin near Bellingham, WA and glaciers on Mount Baker (data source: http://glaciers.research.pdx.edu/glaciers-washington)

adverse effects of land use and climate change pose immediate risks to Tribal rights and their way of life (Colombi 2009; Dittmer 2013). The potential extinction of salmonids from the Nooksack River is unacceptable to the Tribe. The Tribe is dependent on salmon in the Nooksack River, is place-based, and thus cannot move their base to where salmon are located.

2 Recorded trends in climate, streamflow, and glaciers

2.1 Climate trends of the PNW

Climate in the Pacific Northwest (PNW) is dominantly affected by atmospheric-oceanic circulation patterns like the Pacific Decadal Oscillation (PDO) and the El Nino Southern Oscillation (ENSO) because of its proximity to the Pacific Ocean. Within the Nooksack River watershed, elevation rises from sea level to 3,285 m on Mt. Baker over a distance of approximately 53 km. This relatively steep elevation gradient creates substantive orographic effects that intensify these weather patterns. Mean annual temperature has increased 0.8 °C between 1920–2003, with most warming occurring since 1975 (Hamlet and Lettenmaier 2007; Mote 2003). This rate is 50 % greater than the average global warming during the same period (Mote 2003). Between 1920 and 2000, annual precipitation in the PNW increased approximately 14 %, with a 37 % increase in spring, 12 % increase in winter, 9 % increase in summer, and a 6 % increase in autumn (Mote 2003). The intensity of precipitation has slightly increased, and is more prominent during winter months.

The western slopes of the North Cascades receive approximately 1,250 mm of precipitation annually that predominantly falls as snow during the cool season (October–March). This region relies on melting snowpack and glaciers to sustain runoff during the warm season from April–September (Elsner et al. 2010). Snowpack is sensitive to both temperature and precipitation, but temperature is the dominant driver of changes in snowpack and glacier extent (Elsner et al. 2010; Mote et al. 2005; Hamlet et al. 2005; Mote and Salathé 2010). Because of its maritime climate, a large part of the North Cascades that accumulates snow is only a few degrees below freezing during the winter months, making snowpack much more vulnerable to small increases in winter temperature (Stewart 2009). The observed increases in winter temperature have caused more precipitation to fall as rain rather than snow, which has resulted in declining glacier mass balance and altered streamflow regimes (Mote et al. 2008; Pelto 2008; Elsner et al. 2010).

Snowpack is commonly measured as snow water equivalent (SWE, ratio of depth of liquid water to depth of snow containing that water), and is determined near its peak on April 1st. Between 1950–2006, snowpack has declined 25 % in the North Cascades, with the largest decreases at low to mid elevations (<2,000 m) (Mote et al. 2008). Lower elevations (<1,000 m) have experienced decreases in SWE by 40 % or more, and higher elevations (>2,000 m) have experienced decreases in SWE of 15 % to 35 % relative to the 1916–1970 period (Mote et al. 2008). This gradient is strongly correlated with the observed increases in temperature and declines in snow precipitation (Mote 2003; Mote et al. 2005). Casola et al. (2009) and Minder (2010) have estimated that approximately 15 % loss of snowpack occurs per 1 °C increase in air temperature.

2.2 Climate trends in the Nooksack River watershed

Meteorological data has been collected within the Nooksack River watershed at various locations and elevations, with a varied range of record lengths. The Clearbrook weather station has the longest record dating back to 1895, and is located approximately 42 km west-northwest of Mount Baker at an elevation of 20 m. This station is useful for low-elevation climate trends, but is not necessarily representative of the climate conditions affecting the glaciers. Snow telemetry (SNOTEL) stations within the watershed are at higher elevations on the flanks of Mount Baker, yet have shorter record periods making trends, if any, more difficult to discern. The most valuable high-elevation records are those of the Wells Creek and Schreiber's Meadow stations, dating back to 1995 and 1959, respectively. The Wells Creek station (1,228 m) is located on the north side of Mount Baker and Schreiber's Meadow station (1,036 m) is located on the south side. High elevation observations of temperature and precipitation are crucial for assessing meteorological effects on glaciers and streamflow in the lower elevations of the watershed, but longer records are necessary to interpret trends.

Mean annual temperature at Clearbrook has increased 1.4 °C from 1895 to 2010 at a rate of 0.12 °C per decade (OWSC 2012), whereas Wells Creek has only experienced a slight increase (~0.3 °C) in mean temperature from 1995 to 2010 (NRCS2012). Overall, summer temperatures have increased more than winter temperatures, which is consistent with trends in the region. Compared to the state average, the Nooksack River watershed has lower than average summer temperatures and higher than average winter temperatures due to its maritime climate.

Annual precipitation at Clearbrook has decreased by 11 % from 1895 to 2010, with summer precipitation increasing 11 % and winter precipitation decreasing by 26 %. This is not consistent with other regional trends, as winter precipitation has generally increased more than summer precipitation throughout the state (OWSC 2012). Winter precipitation at Wells Creek has also slightly decreased from 1995 to 2010, which is not obvious from 2010 to 2012 when there exists a positive trend in winter precipitation due to the La Nina phase of ENSO. April 1st SWE at Schreiber's Meadow has decreased nearly 26 % from 1959 to 2012, but decreased nearly 31 % prior to La Nina in 2010 (NRCS 2012). This is consistent with trends throughout the North Cascades at elevations below 2,000 m. Longer-term records and higher elevation weather stations are necessary for a more meaningful analysis of climate trends in the Nooksack River Basin.

2.3 Trends in glacier mass balance

Glaciers have long been the most visible and sensitive indicators of climate change and serve as one of the most useful proxies for measuring such change. Regional and local climate affects the magnitude of accumulation and ablation (or loss of ice volume and extent due to melt and sublimation), or mass balance, on a glacier depending on temperature and types and amounts of precipitation. The North Cascades glaciers are losing mass not only because of an extended melting season, but because they are receiving less snow accumulation. Precipitation is more frequently falling as rain rather than snow, resulting in a snowpack that cannot retain meltwater internally by refreezing, thereby reducing the amount of ice lenses and overall glacial ice accumulation (Kaser and Osmaston 2002). Estimates from Granshaw and Fountain (2006) suggest that ice cover in the North Cascades National Park, located approximately 8 km east of Mt. Baker, has reduced by 50 % in the last 100 years. Pelto (2006) states that 75 % of the North Cascade glaciers are rapidly thinning in their accumulation zone and are in disequilibrium with the current climate. The remaining 25 % generally occur at higher elevations and could approach equilibrium under the current climate without further warming. Pelto (2010) concluded that glacial retreat and declining mass balance is ubiquitous, rapid and increasing, with widespread thinning across the entire length of the glaciers suggesting that retreat will continue in the foreseeable future with continued climate change.

Mount Baker is the most northerly stratovolcano in the North Cascades with 12 main glaciers (including two small glacierets) covering an area of 38.6 km^2 and ranging in elevation from 1320 to 3270 m (Pelto and Brown 2012). Approximately 22 km^2 of glaciated area drains into the Nooksack River (Table 1). Pelto and Brown (2012) show that the average retreat of glacier termini has been approximately 370 m over the period of 1979–2009. Mt.

Table 1 Characteristics of Mount Baker glaciers, including retreat from 1979 to 2009, the drainage basin (Middle Fork (MF), North Fork (NF), or Skagit (SK)), and cumulative mass balance (MB) and survival factor (SF) for the period 1990–2008 (Easton and Sholes) and 1986–2008 (Rainbow). Table adapted from Pelto and Brown (2012) and Pelto (2010)

Glacier Name	Area (km^2)	Elevation Range (m)	Aspect (deg)	Retreat (m)	Drainage	Cumulative MB (m)	SF
Deming	4.79	1350–3200	215	−360	MF	–	–
Easton	2.87	1680–2900	195	−320	SK	−9.41	Yes
Squak	1.55	1700–3000	155	−300	SK	–	–
Talum	2.15	1800–3000	140	−240	SK	–	–
Boulder	3.46	1530–3270	110	−520	SK	–	–
Park	5.17	1385–3270	110	−360	SK	–	–
Rainbow	2.03	1340–2200	90	−480	SK	−8.16	Yes
Sholes	0.94	1610–2110	330	–	NF	−10.59	No
Mazama	4.96	1480–2970	10	−410	NF	–	–
Coleman	4.13	1380–3270	320	−340	NF	–	–
Roosevelt	3.57	1584–3270	320	−340	NF	–	–
Thunder	0.81	1870–2490	295	–	MF	–	–
Hadley	0.78	1880–2237	30	–	NF	–	–
Heliotrope	1.68	1885–2362	0	–	MF	–	–

Baker mass balance and accumulation area ratio (AAR) values are generally higher than the rest of North Cascade glaciers because of higher elevations and greater amounts of winter precipitation. As a result, the accumulation zones on Mt. Baker glaciers have experienced minimal thinning, although termini have seen significant retreat (Pelto and Brown 2012). Rainbow, Easton and Sholes glaciers have been observed since 1990, though only the Sholes Glacier drains into the Nooksack River. The mean annual balance of these glaciers has been −0.51 m w.e. from 1990 to 2010, which corresponds to a mass loss of 12–20 %, assuming the mean thickness of is 50–75 m (Post et al. 1971; Harper 1993; Pelto and Brown 2012). Rainbow and Easton glaciers are not experiencing significant thinning in their accumulation zones, suggesting that they are undergoing an equilibrium response to the current climate. Although retreating, they could theoretically approach a new stable position, but it is unlikely. It is uncertain whether the same response applies to future climatic conditions. There are minimal field observations of the glaciers that directly feed the Nooksack River, emphasizing the need for more thorough investigation.

Despite localized differences in glacier behavior, all North Cascades glaciers are responding to regional climate change. Correlation coefficients between each glacier exceed 0.8 indicating a widespread similar response amongst all glaciers (Pelto 2010). This does not depreciate the importance of local orographic effects that control amounts of precipitation delivered to the glaciers. Mt. Baker receives the most snowfall in the North Cascades, which buffers increasingly negative glacier mass balances, relative to other North Cascade glaciers. Precipitation trends in the Nooksack River watershed indicate that winter precipitation is overall decreasing, which is not consistent with regional trends. If this trend continues, glaciers on Mount Baker will accumulate increasingly less snow, ultimately having many implications for mass balance and streamflow.

2.4 Trends in Nooksack River streamflow and temperature

The effects of changes in snow accumulation and glacier mass balance on streamflow in the river have been measured in response to climate change. Studies by Pelto (2008) throughout the watershed compare the historical average discharge of the North Fork (NF) Nooksack River, Middle Fork (MF) Nooksack River, and main stem of the Nooksack River during the ablation season (July–September). From 1963 to 2003, average summer streamflow decreased by nearly 30 % and winter flows increased approximately 1 % (Bach 2002; Pelto 2008). The average decreases in summer flows were 21 % in the NF Nooksack River at Glacier and 28 % in the main stem at Ferndale. Flows in the MF Nooksack River have consistently decreased between 1934 and 2003, but measurements are made below a diversion dam, so trends are not purely representative of climate conditions or glacier behavior. The mean meltwater contribution of high elevation snowpack to summer flow in the Nooksack River basin is estimated to be nearly 30 % of the mean daily discharge (Bach 2002). This estimate is similar to the heavily glaciated Thunder Creek basin in North Cascades National Park (NPS 2012; Pelto 2008). If the current climate trend continues, and glacier mass is absent, there will be 20–30 % less summer flow and spring peak runoff will occur earlier in the year. Mean annual discharge has not significantly increased as a result of increased glacier contribution suggesting that precipitation levels and snowcover are decreasing at approximately the same rate (Bach 2002).

Adverse changes in streamflow caused by climate change also exacerbate stream temperatures. A study by Isaak et al. (2011) and others assessed long-term stream temperature trends in the PNW from 1980 to 2009. They detected a cooling trend in the spring and a warming trend in the summer, fall and winter, with net warming of +0.22 °C (Isaak et al. 2011). Air temperature was responsible for 82–94 % of the variability in stream temperature. These results suggest that many streams in the PNW are responding to climate change (Isaak et al. 2011).

The Tribe has been measuring stream temperatures throughout the Nooksack River watershed since 1999 to establish a baseline and to detect trends in temperature. Data indicates that stream temperatures closely mirror air temperature, but no discernible trends in stream temperatures are evident (NIT 2012). However, this relationship emphasizes that under climate change, when atmospheric temperatures increase, stream temperatures may also increase.

3 Climate projections with climate change

3.1 Climate projections for the PNW

In the PNW, mean annual temperature is projected to increase 1.1–2.9 °C and annual precipitation will likely increase 1.3–3.8 % by the 2080s, averaged and compared to 1970–1999 (Mote and Salathe 2010). Temperature will increase for all seasons, with most warming in the summer months, but changes in precipitation are less certain than changes in temperature (Mote and Salathe 2010). Summer precipitation will likely decrease 14–40 % by 2080s, and winter precipitation will increase on average by only 8 % by the 2080s. There will likely be an increase in frequency and duration of extreme precipitation, though variable in magnitude (Salathe 2006; Rosenberg et al. 2010; Tebaldi et al. 2006), and an increase of 5–10 % in storm intensity for the North Cascades (Salathe et al. 2010). Models project there will be between 27–65 % decrease in annual snowpack by the 2080s relative to the 1971–2000 average (Elsner et al. 2010). By the 2080's, snowpack will decrease 36–71 % below 1,000 m, 25–63 % at mid-elevations between 1,000–2,000 m, and 15–54 % above 2,000 m

(Elsner et al. 2010). The 0 °C isotherm will continue to retreat to higher elevations, resulting in a reduced area of snow accumulation and earlier snowmelt.

3.2 Projections for the North Cascade and Mount Baker glaciers

Those glaciers with accumulation zone thinning, emergence of new outcrops, recession of margins, which includes 10 of 12 North Cascade glaciers with annual measurements, are not forecast to survive the current climate (Pelto 2010). Accumulation area ratio (AAR) observations are frequently below 30 % suggesting a lack of consistent accumulation, which will continue in the foreseeable future (Pelto 2010). Also, those glaciers with the lowest mean elevation have, and will likely experience, the most dramatic changes in volume. Conversely, higher elevation glaciers, like those on Mt. Baker, have the capacity to approach equilibrium with the current climate conditions, though it is unlikely if mean temperature continues to increase. Once glaciers retreat to their accumulation zones, they are substantially less sensitive climate and their retreat rate declines (Hoffman et al. 2007).

If precipitation projections exhibit net increases, higher elevation glaciers may still accumulate significant amounts of snowfall. Although snowpack is projected to decrease overall, it may still remain robust at the highest elevations. Increased summer temperatures will result in higher melt rates, but increased winter precipitation may result in greater snow depth at higher elevations that could potentially buffer the direct melt of glacial ice (Bach 2002). Alternatively, if winter temperatures increase enough to cause precipitation to dominantly fall as rain rather than snow at elevations above 2,000 m, glacial ablation could eventually occur during all seasons, significantly increasing glacier loss. The combined influence of increased temperature and increased precipitation on higher elevation glaciers with climate change is still uncertain because most monitoring has occurred at low to mid-elevations, and downscaling methods are too coarse in scope. There is a perceived inconsistency between the trends seen over the last half century, which indicate that winter precipitation is decreasing, and the projections for the region, which indicate that winter precipitation will increase. This must be addressed with finer-scale downscaling models in order to infer changes to glacier accumulation and its subsequent effect on streamflow and salmon habitat. The Tribe has initiated studies that will focus on higher elevations on the glaciers of interest.

3.3 Projected changes in streamflow

As a result of changes in the timing of precipitation, declining snowpack, and glacier retreat, streamflow timing will likely shift significantly to earlier spring runoff. Increases in stream temperature are also expected as there will be less snow and ice contribution to summer runoff (Elsner et al. 2010). Summer baseflows in the PNW will initiate earlier in the summer and will diminish further into late summer and early fall. The warm season (April to September) runoff is projected to decrease by 16–19 % by the 2020s, 22–28 % by the 2040s and 34–43 % by the 2080s (Elsner et al. 2010). This will result in depleted Pacific salmonid summer and fall habitat due to reduced quality and quantity of flow, which limits spawning and rearing habitats and overall ecosystem health. The degree of adverse impact will depend on the specific species, stock, and life stage. By 2040, 16 watersheds in the Cascades, including the Nooksack River watershed, are characterized as critical basins with water shortages for fish habitat that will experience a significant to severe impact on summer low flows (Fig. 2). The cool season (October to March) runoff is projected to increase by 10–13 % by the 2020s, 16–21 % the 2040s and 26–35 % by the 2080s as a result of projected increased winter rain precipitation and melting snowpack. Because of increased winter

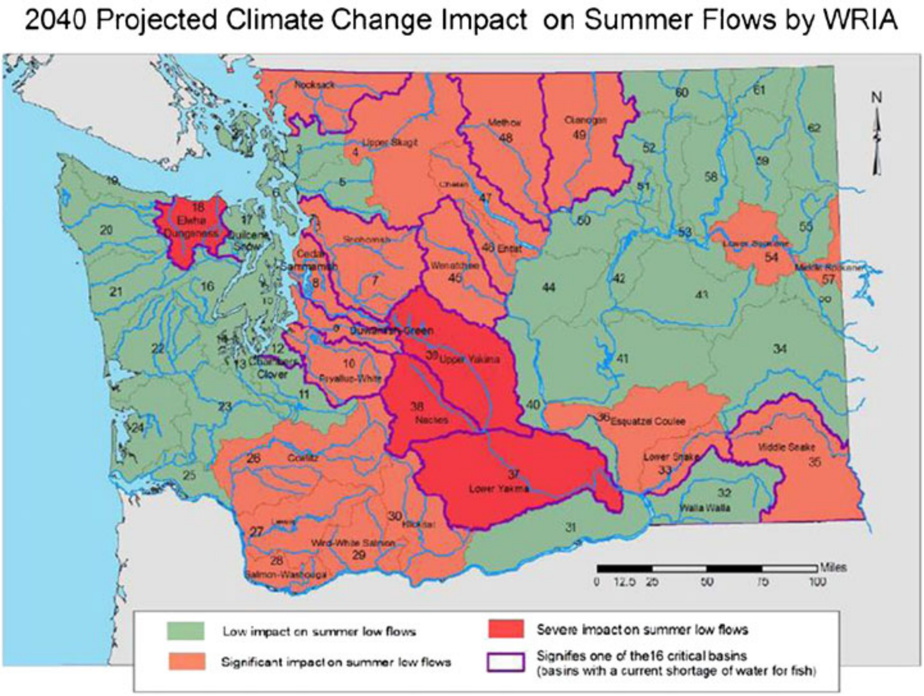

Fig. 2 Projected impact of climate change on summer low flows by the year 2040 for major watersheds in Washington State (From WTAGBI Report 2010)

flows, the total annual streamflow is expected to increase on average across the state by 0–2 % by the 2020s, 2–3 % by the 2040s, and 4–6 % by the 2080s (Elsner et al. 2010). Though modest, these changes will be primarily driven by increases in winter precipitation, regardless of whether it falls as rain or snow.

Dickerson and Mitchell (2012, in review) have modeled the effects of climate change on streamflow in the Nooksack River watershed, where they simulated future streamflow in the entire Nooksack River watershed by utilizing a range of future climate conditions produced by GCMs. Their results from three model simulations predict that a substantial increase in winter (30 to 97 % increase), spring (23 to 32 % increase), and fall (21 to 30 % increase) streamflow, and a substantial decrease in summertime flows (up to 40 % decrease) will likely occur by the year 2075. The Climate Impacts Group (2013) downscaled models suggest similar changes in streamflow. Spring snowmelt peak runoff will likely shift to earlier in the year and eventually combine with the winter peak runoff generated by rainfall as the snow-dominant portion of the watershed trends toward a transitional watershed, and the transitional portion of the watershed trends toward a rain-dominant watershed. Thus, the shape of the hydrograph will change, with one broad peak occurring from December through May, and quick recession to baseflow levels in July. As such, baseflows will initiate earlier in the summer and extend through October.

The glacial melt contribution to streamflow will eventually decrease as atmospheric temperatures increase and glacial extent decreases (Dickerson and Mitchell 2012, in review); however, the proportion of the summer baseflows contributed by glacier melt will increase due to reduction in precipitation in the summer time with climate change (Riedel and

Larrabee 2011). Seasonal snowpack, however, has the most control of streamflow in a changing climate. Simulations indicate that maximum SWE will decrease through time and shift to earlier in the season resulting in earlier spring melt peak, which is consistent with other regional research (Elsner et al. 2010; Mote and Salathe 2010; Hamlet et al. 2005). Additionally, warmer winter temperatures will lead to more rain-on-snow events that cause more frequent and higher peak flow events (Dickerson and Mitchell 2012, in review).

Mitchell (2013) found that the glacial meltwater component of late summer streamflow in the MF Nooksack River varied considerably for a range of climate conditions and scenarios. Glacier meltwater contribution was between 8.4 % and 26.1 % of total flow for the present climate conditions and 33.7 % for the predicted climate conditions. The results of the study further suggest that late-summer runoff could be reduced by anywhere between 3.1 % and 8.6 % as a result of a 17 % reduction in glacier size predicted for the next 50 years, and a reduction ranging from 6.7 % to 19.4 % as a result of a 48 % reduction in glacier size predicted for the year 2150. Overall, there will likely be an increase in glacier melt contribution to summer baseflows, followed by a substantial reduction once the glaciers entirely recede.

Similar studies have been conducted in other PNW watersheds that quantify the glacier melt contribution to streamflow. Pelto (2011) assessed glacier retreat and summer runoff in the Skykomish River Basin in Washington from 1950 to 2009 and found that the 45 % reduction in glacier area over this period led to a 38 % reduction in glacier runoff. The decline in glacier contribution to river discharge was only pronounced during low flows in late summer. A study conducted in the Hood River Basin of Oregon showed that 41–73 % of late summer streamflow is derived from glacier melt (Nolin et al. 2010). The study found that although projected temperature increase will increase glacier melt contribution to streamflow, widespread glacier recession will ultimately lead to substantial declines in streamflow during the summer months. However, glacier runoff will stay the same or increase if the glacier-covered area decreases <15 % for every 1 °C increase in temperature (Nolin et al. 2010). The methodologies of these studies should be incorporated into future research and planning in the Nooksack River watershed to fully assess the impact of climate change on glacier ablation, streamflow, and subsequent loss of fish habitat. The Tribe is implementing studies on Mt. Baker glaciers to better determine their behavior in response to recent climatic trends and subsequent climate changes in regard to glacier melt contributions to the Nooksack River.

4 Implications for salmonids

The Nooksack River watershed supports nine species of salmonids including populations of Chinook (spring and fall), riverine sockeye, chum, pink (even- and odd-year), and coho salmon, steelhead/rainbow, cutthroat, and bull trout, and Dolly Varden (WRIA1 SRB 2005). The abundances of two spring Chinook populations are critically low, on the order of 100–300 natural-origin spawners for each population. The populations comprise two of 22 independent populations in the Puget Sound Chinook ESU's; both populations are considered essential for recovery of the ESU (WRIA1 SRB 2005; WDFW 2002). It is clear that abundances of several local salmonids populations have diminished substantially from historic levels (WRIA1 SRB 2005), as only two of 16 salmonid stocks identified by Washington State Salmonid Stock Inventories are currently considered healthy (WDFW 2002). Further, although direct counts are not available, it appears that native salmonid runs are less than 2 to 8 % of the runs in the late 1800's (Lackey 2000).

Habitat degradation is the leading cause of decrease in salmonid populations in the Nooksack River watershed. Both decreasing summertime stream flows as a result of decreased glacier melt contribution and increasing stream temperatures with climate change will further reduce habitat and stress salmonids. Low summer flows will cause a lack of deep pools and side channels for thermal refugia, and will cause even further warming of stream temperatures alongside the warming due to increased air temperatures. Periods of high flow due to increased glacier-melt during warm summers will cause increased sediment load (particularly fine sediment), redd scour, and altered stream networks that may disconnect side channels thereby stranding juveniles. Spring Chinook are of particular concern to the Tribe and are especially limited by these factors because they are the most endangered (WRIA1 SRB 2005). Predicted decreases in summertime low flows will further reduce available habitat by 10 % for spring Chinook during the summer holding period based on weighted usable area habitat curves presented by WRIA1 (2000). Climate change-induced increases in frequency of rain-on-snow events and intensity of precipitation events during the winter may cause debris-flow events that result in channel and habitat changes that further adversely effect salmonids.

Increased air temperatures as a result of climate change combined with deteriorating riparian cover as a result of land-use will produce higher water temperatures that are lethal to salmonids. Water temperature has already increased alongside population growth in the area, yet climate change has exacerbated this dynamic. High water temperatures during summer represent an important limiting factor for spring Chinook and other salmonids in the Nooksack River watershed, especially in the South Fork of the Nooksack River, which is a Clean Water Act (CWA) Category 5 303(d) listed for high temperatures. High water temperatures in the South Fork frequently exceed optimal temperature ranges and approach lethal limits for salmonids (WRIA1 SRB 2005). Stream temperatures frequently exceed 20 °C, and sometimes exceed 24 °C well in excess of the temperature ranges considered optimal for Chinook incubation (11–15 °C) and juvenile rearing (14.2 °C –16.8 °C) (Beechie et al. 2012). High temperatures stress holding and spawning fish, and increase susceptibility to disease, which can cause pre-spawn mortality or otherwise reduce reproductive success (WRIA1 SRB 2005). Continued increases in stream temperatures and reduced meltwater from glaciers with climate change will further stress all nine species of Nooksack River salmonids during all of their life history stages including migration, holding, spawning, intra-gravel development, rearing, and out-migration (Currence 2013). Spring Chinook salmon are especially susceptible to further habitat loss and are particularly important to the Tribe for cultural, subsistence, and commercial uses. Thus extinction of this species is not an option.

Continued increases in heat loading and reduced contribution of snow and ice melt to streams will result in increased water temperatures in the PNW with subsequent impact on aquatic habitats. Statewide, the annual maximum average water temperature will likely raise 1 °C by the 2020s, and 2–5 °C by the 2080s (Mantua et al. 2010). These projections suggest that stream temperature will increase at rates 50–100 % faster than recent decades (Mote et al. 2008; Mantua et al. 2010). According to Poole et al. (2001) and Mantua et al. (2010), stream temperatures in the Nooksack River watershed that are favorable for salmon under the current condition will transition to stressful habitat; and areas that were stressful for salmon will transition to fatal areas. The temperature increases would push temperatures in excess of the optimal and lethal thresholds and the duration of exceedances would likely increase, both of which would pose challenges to the survival and persistence of salmonids. Habitat quality and quantity will continue to decline as summer flows decrease and water temperatures increase, ultimately disrupting the timing of spawning and migration of salmonid species and increasing competition for habitat. As such, reducing the exacerbating effect of human activities and climate change, and implementing effective restoration activities will be fundamental to the survival of salmonids.

Beechie et al. (2012) have evaluated a menu of restoration techniques in the face of climate change and developed a decision support process for adapting salmon recovery plans that incorporates (1) local habitat factors limiting salmon recovery, (2) scenarios of climate change effects on stream flow and temperature, (3) the ability of restoration actions to ameliorate climate change effects, and (4) the ability of restoration actions to increase habitat diversity and salmon population resilience. They found that restoring floodplain connectivity, restoring stream flow regimes, re-planting deforested riparian zones, and re-aggrading incised channels are most likely to ameliorate stream flow and temperature changes and increase habitat diversity and population resilience. Restoring riparian shading along important salmon-bearing streams will be essential to ameliorating increased stream temperatures since current riparian shading is well below that needed to ameliorate high temperatures (Coe 2001). Given that conditions for salmonids in the Nooksack River watershed could transition from favorable to stressful with climate change, as opposed to lethal (Mantua et al. 2010), there is a likelihood that restoration actions could increase the probability of salmon survival in the face of climate change. However, planning for such restoration adapted to climate change must occur immediately to have the benefits of restoration in place before climate change has a substantial effect on stream temperature and flows.

Determining which restoration tools are most effective in the face of continued climate change will be essential to effective and successful restoration following a similar approach to Beechie et al. (2012). Further, climate change is beginning to be considered in temperature TMDLs, such as the South Fork Nooksack River TMDL, but such studies are limited by existing technology and protocol. The EPA and the Tribe (Klein et al. 2013) have initiated a pilot research project that is focused on how to evaluate, design, and implement restoration tools in a temperature TMDL that will address the increase in stream temperatures, loss of glacier melt contributions, decreased baseflows, and increased winter-time flows that adversely affect fish and habitat. This is one of a very few such projects being implemented in the United States. The outputs of the pilot research project will be a set of recommendations that will inform development of the TMDL, and that recommends updates to salmon recovery planning and other land use and restoration planning efforts taking climate change into direct consideration.

5 Conclusions

The Nooksack River is fed by snow and glacier melt that provides critical water resources that support Pacific salmonids. Climate trends generally show an increase in temperatures throughout the year and an increase in precipitation during the winter and spring, less overall snow accumulation, earlier snow melt and runoff, and reduced baseflows. There are significant trends in glacier loss at low elevations, with more negative balances for glaciers below 2,100 m. Lower elevation glaciers are at a greater risk of disequilibrium, but higher elevation glaciers, like those on Mt. Baker could theoretically approach equilibrium with current climatic trends. Because of Mt. Baker's unique response to regional climate trends, it is crucial that future investigations focus on higher elevation climate conditions and develop models that will constrain glacier response to future climate scenarios in the Nooksack River basin. This will allow more accurate predictions of reduced stream flows and integrate those effects with increased stream temperatures.

Existing temperatures during the summer and early fall already reach stressful levels for all nine salmonid species in the Nooksack River. With climate change, increased stream temperatures are predicted that could push temperatures to the lethal level for salmonids. Effective watershed restoration will be essential to promote the survival, persistence, and recovery of salmonids in the face of climate change. The most effective watershed restoration tools include: re-establishment of riparian forests, reconnection of floodplains, and reintroduction of large woody debris in the stream that will facilitate resilient channel response to changes in hydrology, sediment input, and temperature brought on by climate change. Such restoration should be implemented as soon as possible so that the effects of such restoration will be in place by time climate change causes challenging conditions for salmon, particularly spring Chinook salmon. Since the Tribe is place-based and cannot relocate to where the salmon will be, the extinction of salmonids from the Nooksack River is unacceptable. The Tribe has been collaboratively working with various governmental agencies and scientists regarding climate change effects on the hydrology of the Nooksack River so that restoration efforts can reduce the chance that continued climate change will cause extinction of salmonids from the Nooksack River.

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DOI 10.1007/978-3-319-05266-3_13
Reprinted from *Climatic Change* Journal, DOI 10.1007/s10584-013-0783-7

ESSAY

Re-thinking colonialism to prepare for the impacts of rapid environmental change

Nicholas James Reo · Angela K. Parker

Received: 19 November 2012 / Accepted: 28 April 2013 / Published online: 4 June 2013

Abstract This essay demonstrates how key concepts from ecology can be applied within historical analyses in order to gain insights regarding contemporary environmental change. We employ a coupled human and natural systems conceptual framework in a nascent historical analysis of rapid societal and environmental change in colonial New England, where European colonization led to stark and rapid transformations. Introduced diseases reduced indigenous communities to a fraction of their pre-contact levels. European agriculture and associated pest species, deforestation and overharvest of ecologically influential species were among key aspects of the rapid changes in colonial New England. Cross-continental biotic introductions initiated reinforcing feedback loops that accelerated the transition of human and natural systems into novel states. Integrating colonial history and ecology can help identify important interactions between human and natural systems useful for contemporary societies adjusting to environmental change.

1 Introduction

Recent and projected climatic change could lead to the most drastic, rapid environmental changes in North America since those that followed European colonization. Yet colonial history has rarely been studied for insights applicable to current environmental change problems. In this essay, we suggest that new and existing research on environmental and colonial history can generate insights applicable to current mitigation and adaption efforts in the face of rapidly changing environments. We briefly explore an example of this new line of inquiry, examining existing scholarship on New England's colonial history for lessons concerning human responses to rapid environmental change. We engage history and ecology to show how partnerships between historians and scientists studying linked social and

This article is part of a Special Issue on "Climate Change and Indigenous Peoples in the United States: Impacts, Experiences, and Actions" edited by Julie Koppel Maldonado, Rajul E. Pandya, and Benedict J. Colombi.

N. J. Reo (✉) · A. K. Parker
Dartmouth College, Hanover, NH, USA
e-mail: Nicholas.J.Reo@Dartmouth.edu

ecological change can lead to fruitful strategies or diagnoses for environmental change mitigation and adaption. Our goal is to use this Special Issue of *Climatic Change* as a forum for *preliminary* remarks and to introduce a form of inquiry worth further exploration.

In our nascent analysis, we consciously avoid making a point-for-point comparison between the early colonial era and today. Such a task could prove fruitless given the vastly different circumstances between the early colonial venture—which focused on (1) the quick-and-dirty extraction and exploitation of plant and animal resources, (2) gaining land base for settlements, and that (3) succeeded in large part due to the rapid depopulation of indigenous communities—and today's environmental change trajectories, which are themselves the progeny of this earlier time period. Rather, our preliminary example gains traction and relevancy by leveraging key concepts from ecology within an historical analysis in order to gain insights applicable in contemporary settings. Specifically, we look at the concepts of coupled human and natural systems, feedback loops and tipping points, all notions that are currently used by ecologists and others studying linked social and ecological issues. We look back in time to understand the effects of rapid environmental change on coupled human and natural systems; we identify social and ecological tipping points and try to explain the ways that feedback loops can both amplify and mitigate environmental change.

To date, researchers have responded to global environmental change and rapidly changing local environments by *forecasting* future change via predictive models and *backcasting* to determine pathways to desirable future outcomes. Backcasting involves imagining a desired future scenario, then planning the steps that could achieve that vision. De Young and Princen (2012) describe this process as *prefiguring* "the needed institutions, economies, physical structures, norms, and behaviors necessitated by biophysical constraints." While forecasting and backcasting are indispensible, this paper suggests the relevancy of a third approach: using historical analysis to study linked ecological and societal consequences of rapid changes.

Indeed, research using this third approach already exists. For instance, paleo-ecologists undertook synthetic research investigating coupled human and natural systems change over long timescales (Delcourt and Delcourt 2004); environmental historians investigated ecological change (e.g., Cronon 1983) and consequences of environmental change for societies (Davis 2002; Sandlos 2007); and cultural anthropologists examined the social, cultural, political and economic impacts of, and responses to, rapid socio-ecological change (e.g., Colombi 2012; Wenzel 2009). Colombi's work (e.g., Colombi 2012; Colombi and Smith 2012) in particular examines tribal historical narratives to understand how tribal societies develop adaptive capacity and other cultural-level responses to continual socio-ecological change. A 2012 special issue of the Proceedings of the National Academy of Sciences Sustainability Science section (Butzer and Endfield 2012) explores historical examples of linked social and ecological change and contemplates lessons for contemporary societies. Endfield (2012) looked at societal resilience and adaptive capacity to climatic variability (drought) in colonial Mexico. With these recent works in mind, our paper highlights the contribution colonial Native American and environmental history can make in identifying mitigation and adaptation strategies needed for addressing various forms of contemporary, rapid environmental change.

2 Key ecological concepts and contemporary environmental change

2.1 Coupled human and natural systems

Humans have always interacted with natural systems. Increasingly, scholars interested in the interplay between ecology and society view humans as *integral components* of ecosystems.

Recognizing the continuous webs of interactions between societies and their surrounding environments, researchers from various disciplines have begun using the term coupled human and natural systems (CHANS) to describe any "systems in which the human and natural components interact" (Liu et al. 2007). Researchers studying rapid environmental change are some of the earliest adopters of CHANS-oriented conceptual frameworks (e.g., Mastrandrea and Schneider 2004; IPCC 2007). A key feature of CHANS research orientations is the explicit investigation of the "couplings", i.e., the reciprocal interactions between linked human and natural systems (Liu et al. 2007). For example, Murray et al. (2013) used a CHANS conceptual framework in their study of the interconnections between coastal economics and physical coastline change in the context of rising sea and storm surge levels.

2.2 Feedback loops

The feedback loop concept provides one way of understanding reciprocal interactions between humans and the environment. Positive feedbacks occur when changes in an environmental or societal condition cyclically amplify or enhance that condition; negative feedbacks serve to interrupt or slow those changes. Feedback loops can be relatively direct or involve several steps.

Feedback loops are central to understanding complex human-environment interactions in the context of rapid environmental change. For example, in the American West, anthropogenic climate change creates expanded habitat for native bark beetle species, resulting in unprecedented beetle outbreaks. Increased tree mortality from these outbreaks can turn forests from small net carbon sinks to large net carbon sources due to decreased carbon uptake by trees, increased short term carbon emissions from wildfire, and increased future carbon emissions from decaying trees (Kurz et al. 2008). Such changes in the flow of carbon will contribute to global atmospheric CO_2, and ultimately to global warming, thereby amplifying the cycle of effects (i.e., generating a positive feedback loop).

Feedbacks directly involve societal factors and economic variables. For example, widespread bark beetle outbreaks could create new operational costs and/or timber revenue losses (Waring et al. 2009), limiting available finances for mitigation activities such as selective forest thinning and creating a positive feedback. Negative feedbacks can come in the form of management actions designed to mitigate the deleterious effects of climate change, or promote resilience of these systems to shocks and disturbances, like pest outbreaks or wildfire. Spies and colleagues (2010) suggest several ways to create interrupting feedbacks to slow or reverse impacts of climate change on forest ecosystems and associated wildlife, such as altering landscape structure to facilitate the flow of organisms and impede the spread of fire and pathogens.

2.3 Thresholds

Normally, change occurs within societies and natural systems somewhat predictably through steady trends and/or somewhat bounded fluctuations around an average condition. However, systems exhibiting slow, steady change and normal fluctuations can suddenly experience rapid changes. Thresholds are sudden transitions between alternate regimes in ecosystems or coupled human and natural systems (Scheffer et al. 2001; Liu et al. 2007). These transitions are also referred to as "tipping points". For example, on the Grand Portage Reservation in Northeast Minnesota, USA, steadily rising water temperatures in an inland lake have contributed to the transition from a cold water, brook trout fishery to a cool water, yellow perch and walleye fishery. Brook trout habitat progressively degraded because of rising temperatures; once lake temperatures rose above a critical threshold, trout could no longer survive. In this instance, the Grand Portage Band of Lake Superior Chippewa Indians was able to anticipate this biological threshold, and facilitated the fisheries transition by shifting their stocking program to cool water species to ensure a steady flow of subsistence resources (ITEP 2012). Lin and Peterson (2013) suggest that it may be necessary to guide transitioning systems across climate boundaries towards states that are socially and environmentally desirable, as was done by the Grand Portage Band.

3 Linked environmental and social change in colonial New England

The success of the colonial venture in the northeastern United States—or "New England"—created a cascade of environmental and human change across North America. As such, the northeastern forest holds an important place in the creation story of the United States and deserves close examination for the interplay between human and environmental change. While the success of this colonial history nearly drowns out the experiences of indigenous peoples like the Abenaki, Mohegan, Pequot, Narragansett, Wampanoag, or Passamaquoddy, their indigenous history provides a crucial case study of environmental and demographic change due to European colonization that is instructive for our shared future of rapid environmental change.

3.1 Pre-contact coupled human and natural systems

Prior to the arrival of Europeans, old growth deciduous forests, rich with animal and plant resources, covered over 80 % of what is now known as "New England." Indigenous work and use patterns encouraged and shaped this biodiversity, as over millennia Native communities learned to rely on diverse plant and animal sources for food, clothing, medicine and shelter. Pre-contact indigenous land tenure systems involved "very intense local management" (Russell 1980), and activities included using light ground fires to encourage the proliferation of useful plant and animal populations. Fire was also used to clear underbrush, thin canopy cover, discourage plant diseases and pests and to increase the rate of soil nutrient cycling (Cronon 1983; Conforti 2011). Indigenous communities shaped disturbance regimes across the pyric portions of the landscape through selective use of prescribed burns. Their efforts to create a diverse patchwork of habitat for favored species helped maintain a wide array of ecosystems at various stages of succession.

Besides such burning practices in forests and wetlands, indigenous people also used fire to clear and maintain lands for cultivation in climatically favorable portions of New England. By the 14th century, many northeastern indigenous communities adopted the three sisters cultivation system, a polycultural cropping system intermixing varieties of corn, bean, and squash. The three sisters system allowed legumes to fix nitrogen in the soil as both beans and squash covered the ground to limit soil moisture evaporation and the growth of weeds. This successful cropping system diversified northeastern landscapes to create larger forest openings and a greater amount of edge habitat. Far northern tribes continued a hunter-gatherer work model due to short growing seasons, but most tribes in the northeast developed labor patterns necessary to create and maintain clearings for large gardens. They also developed sedentary settlements necessary to tend cornfields that, without constant labor, easily submit to pests, weeds, and drought (Conforti 2011; Smith 2007; Taylor 2001). Indigenous communities in New England avoided rapid depletion of soil nutrients in their gardens through the combination of annual burning, companion planting with nitrogenfixing legumes, leaving fields fallow, and selecting sites for cultivation with optimal climatic and soil conditions (Bennett 1955; Thomas 1976).

By the time Europeans arrived, New England was a densely populated region where indigenous communities reaped the benefits of their active land tenure systems from fields to forests. It was a world where, as Narragansett leader Miantonomi described, Native communities “had plenty of deer and skins, our plains were full of deer, as also our woods, and of turkies, and our coves full of fish and fowl” (Calloway 1994).

3.2 Contact and rapid demographic change

Before permanent European settlements, the northeastern forests experienced the shock of human depopulation. Epidemic disease intensified with greater contact between Europeans and indigenous communities. The first recorded epidemic in 1616 killed so many people that colonists encountering the scattered skeletons a few years later described the aftermath of bare bones and skulls as “a new found Golgotha” (Cronon 1983). The unburied bones indicated extreme social disruption and few remaining survivors (Calloway 1997). Severe human depopulation meant that cornfields went untended, forest underbrush went unburned and animals and fish were not hunted. Colonial settlers took over the abandoned cornfields of depopulated Native villages, benefiting from earlier indigenous labor and land management practices (Russell 1980).

As epidemic disease cycled through and nearly annihilated northeastern indigenous communities, other opportunistic species irrevocably changed the landscape. Alfred Crosby’s description of “ecological imperialism” includes the introduction and rapid spread of weeds and animals such as cattle, pigs, rats, and honeybees. These species undermined indigenous agricultural traditions, from sowing to planting to harvesting and storage (Crosby 1986; also Anderson 1994; Cronon 1983).

Into a landscape recently depopulated by epidemic disease, approximately 21,000 colonists entered New England from 1630 to 1642 as part of the Great Puritan Migration. By 1670, colonists had organized approximately 70 towns and with a population of 52,000 outnumbered Native people by three to one in southern New England (Conforti 2011; Taylor 2001). This large immigrant community was hungry for land. They were also just plain hungry (Grandjean 2011), and they alleviated both types of hunger through the aggressive pursuit of property and corn.

3.3 A tipping point for New England CHANS

The time period between the Pequot War (1636–38) and King Phillip’s War (1675–76) became a tipping point in the shift from indigenous to European prominence in southern New England. This demographic shift brought with it a transition from indigenous to European land tenure practices. Colonists replaced soil-building and diversity-promoting indigenous practices with rooting, trampling and foraging domesticated animals, agricultural pests and soil-degrading agriculture. Miantonomi, the Narragansett leader, who in 1642 described the bountiful pre-contact forest, recognized the implications of the change in land stewardship, stating “[b]ut these English have gotten our land, they with scythes cut down the grass, and with axes fell the trees; their cows and horses eat the grass, and their hogs spoil our clam banks, and we shall all be starved” (Calloway 1994).

The settlers’ quest for land and resources was motivated by their need to reinforce Eurocentric cultural and religious beliefs and their struggle to survive in the New England landscape. They employed multiple strategies to extend territorial control, including the use of violence and subversion of a wampum tribute system to gain influence in the fur trade. For example, the Pequot War of 1636 originated in a time of scarcity as colonial populations ballooned. The war began with corn raids and a demand for wampum tribute and culminated with a massacre. After the war, surviving Pequots were driven off their lands, sold into slavery or incorporated into other tribes. Tribes who collaborated with the English against the Pequot signed the 1638 Treaty of Hartford and became tributaries to colonists, allowing the English to justify incorporating their allies and their allies' lands into "New England" (Lipman 2008). Such English victories—along with a ballooning European population in the region—allowed them to consolidate European land tenure systems in southern New England.

King Philip's War (1675–1676) 40 years later confirmed the ascendency of European land tenure. Tribes who allied with the English or avoided involvement in the Pequot War began to bridle under the yoke of English control. Wampanoag and Narragansett violence targeted the "churches, houses, fences, barns" and livestock with which the English colonists had transformed the northeastern landscape (Taylor 2001). When Indian resistance could no longer be sustained, Puritans answered with bloodshed, executing or enslaving communities that rebelled and were unable to escape to New France. At the end of King Philip's War, indigenous resistance was no longer a viable option in southern New England.

Following King Philip's War, the European demographic climb accelerated. The 52,000 colonists inhabiting New England in 1670 grew to 92,000 in 1700, while the indigenous population ebbed to approximately 10 % of the southern New England population by 1680 (Pulsipher 2007). Although the Native people in northern New England were less severely outnumbered, by the end of King Philip's War, the entire Native northeast was in jeopardy politically and culturally. And while northern New England tribes would continue to exert significant diplomatic and territorial influence through the first half of the eighteenth century (Baker and Reid 2004), the colonial governments to the south diminished indigenous political and economic power throughout the region.

This 40-year period between Pequot War and King Phillip's War radically altered the New England landscape and ushered in new socio-political, ethnic and ecological regimes. In so doing, it constituted a tipping point for CHANS in colonial New England. The transcendence of the colonial enterprise initiated or reinforced several key environmental disruptions, including the removal of indigenous populations and their land use practices, the establishment of European-style agriculture and associated pests and removal of important animal species and forest cover. These interconnected disruptions rapidly accelerated the transformation of New England into a novel biophysical and cultural landscape.

3.4 Amplifying feedbacks in colonial CHANS

Massive depopulation due to epidemic disease frames each of the subsequent changes to the coupled human and natural systems in New England. With fatality rates estimated between 70 and 90 %, villages along the eastern seaboard were forced to re-form community groups out of the fragmented remaining populations. Both depopulation and the fragmentation of community groups endangered cultural knowledge and practices (e.g., language, religion, agriculture and hunting). The extreme cultural and demographic loss also meant that indigenous communities became increasingly vulnerable to emergent European colonial ventures. As European populations climbed, indigenous communities were increasingly exposed to disease (Conforti 2011). Continued indigenous depopulation cleared the way for expanding colonial settlements, creating opportunities for more disease outbreaks. This cycle was a positive feedback loop that rapidly accelerated demographic change within New England (Fig. 1a).

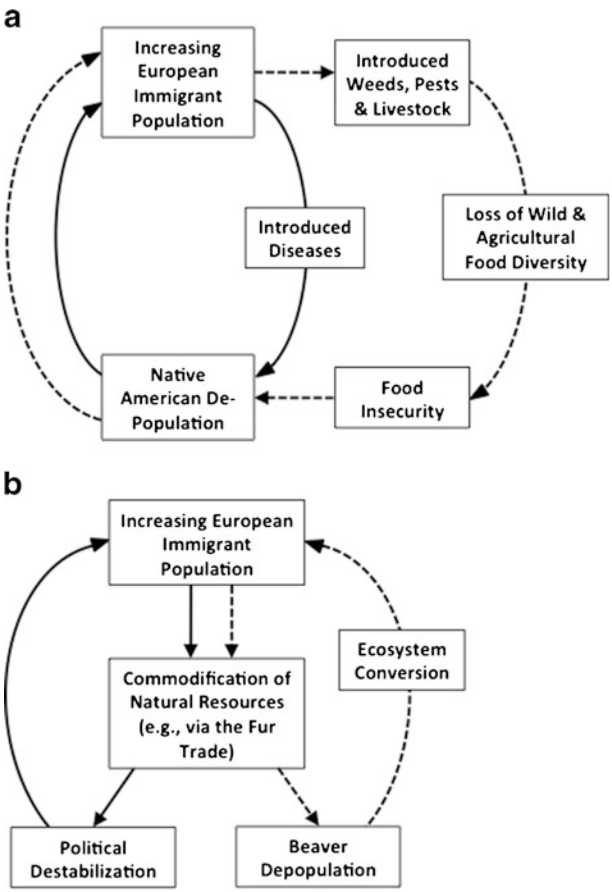

Fig. 1 Positive (i.e., reinforcing) feedback loops in coupled human and natural systems of colonial New England. **a** depicts two separate feedback loops indicated by the *solid* and *dashed lines* as does **b**

The spread of European weeds, pests and domesticated livestock constituted a second environmental shock. Tough weeds associated with European livestock quickly and persistently covered any cleared ground; rats came ashore with colonists and wrecked havoc in indigenous fields and storage caches; colonists allowed their hogs and livestock to roam free and graze upon Native food sources in crop fields, meadows and shorelines. Especially as European populations swelled, repeated intrusions of colonists' livestock ensured constant low-level conflict between indigenous and colonial communities. Native agriculturalists and European animal owners sought compensation for fields destroyed or animals killed or held hostage in retaliation (Cronon 1983). Culturally, the biotic invasions jeopardized indigenous food cultures, including long standing relationships with wild and cultivated plants and animals, deep knowledge about local ecosystems and cultivation systems, ethics guiding their harvest behaviors, and spiritual beliefs and ceremonies. Politically, the cumulative tide of invasive species challenged the food security of already beleaguered indigenous communities. As many historians of Native New England during the colonial period have noted, the challenge to Native food systems resulted in weakened populations that were ever more vulnerable to political and economic oppression—which in turn led to increased mortality or out-migration from New England (Fig. 1a).

The removal of ecologically and economically vital species, including the North American beaver, also exacerbated interconnected political and environmental change. Beginning in the very early contact period within the larger northeast, as indigenous communities depleted local beaver populations, hunters expanded into neighboring territory; concurrently, colonial powers sought allegiances with tribes to maintain the flow of furs. European traders inundated Native communities with goods produced by others, such as guns, in order to stimulate the harvest of beaver through intensive Native labor (Rothschild 2006). As indigenous communities found themselves increasingly involved in the extractive economy, their political lives became much more fraught and warfare shifted towards aggressive territorial expansionism. These dynamics intensified intertribal conflicts that, while concentrated further west (Richter 2000), impacted the entire northeastern region through the proliferation of violence and unstable allegiances throughout the entire colonial period (Lipman 2008).

In addition to such socio-political ramifications, the near-eradication of beaver transformed the ecology of the northeastern forest. Beaver dams create habitat for fish, waterfowl, and mammals that gather to use the collected water (Cornell 1990), so beaver population crashes impacted entire ecosystems and associated biota. These changes also meant a loss of wild game and food plants important in traditional diets of Algonquian peoples. In this way, overharvesting beaver reduced the availability of traditional foods, amplifying rapid changes in Algonquian food systems. Further, as beaver dam impoundments receded, colonizing Europeans easily converted newly exposed, nutrient rich meadows to agricultural fields (Cronon 1983; Penna 1999; Irland 2011). Settler conversion of newly formed meadow ecosystems into agricultural uses further reinforced colonial dominance and accelerated the transformation of CHANS in New England (Fig. 1b).

Within a few hundred years of colonization, the exploitation of forests to support Atlantic trade and the expansion of colonial settlements irrevocably altered the New England landscape. New England was transformed from a heterogeneous patchwork of ecosystems supporting diverse food systems into a comparatively depauperate hash of fields and forests susceptible to pest outbreaks and erosion. The cascading effects of the initial human depopulation, biotic invasions, loss of key species and deforestation, driven by a new extractive economy, created political, cultural, and environmental chaos for Native peoples.

4 Discussion

The primary goal of this paper is to introduce a line of inquiry looking at colonial period socio-ecological change for insights to help societies better cope with contemporary environmental change processes. *What difference did it make to look at this history through the lens of key ecological concepts?* First, by adopting a CHANS conceptual orientation in our historical analysis, we were better able to hone in on the reciprocal interactions between human and natural systems. The colonial period was a chaotic clash of cultures that resulted in complex demographic, cultural, political, social and environmental changes. Our CHANS orientation helped quiet the noise in the chaotic colonial history of New England so that we could see important socio-ecological linkages. Key among these linkages were amplifying feedback loops that quickly accelerated the changes afoot, ultimately leading to a tipping point in various regime shifts (e.g., ecological, political, demographic and economic) within New England CHANS by the close of King Phillip's War in 1676.

Future work using this sort of approach could help us deal with contemporary environmental change. Multi-disciplinary historical analyses such as we have demonstrated could highlight how contemporary societies have a comparative wealth of tools and options for dealing with environmental change. Despite their deep knowledge of local environments, the indigenous peoples of New England had very little opportunity to slow the changes occurring in their homelands. In the face of severe human depopulation and its associated socio-cultural impacts, followed by widespread environmental degradation and impacts to indigenous food systems, the original peoples of New England had little footing from which to push back against the flood of changes. Thinking of our current environmental change dilemmas in the shadow of the rapid, transformative changes that accompanied colonialism is an alarming process that could awaken reluctant decision makers into action. For instance, our nascent analysis brings into high relief the dramatic effects of cavalier cross-continental species introductions and rapid changes in land tenure regimes and land use. Part of the utility of this form of research is revealed in these dual functions of awakening decision makers and highlighting the relative breadth of options available to contemporary communities.

When indigenous communities were decimated by disease and eventually alienated from their known environments, land tenure innovations based on deep, local ecological knowledge, disappeared. Colonists—and their extractive systems aimed at key animal and plant species—became the new shapers of cultural landscapes, but with their relatively short histories in North America, their land use decisions were made in the absence of long-term local ecological knowledge (see Davis 2002 for non-North American examples). Rapid ecological degradation subsequently ensued, and New Englanders created a difficult project of stewarding a far less resilient landscape without help from indigenous land managers who would have known best how to enact ecological restoration measures (i.e., negative feedbacks).

Today, we can leverage different sources and types of knowledge, including local ecological knowledge, to mitigate and adapt to climate change. Resource practitioners who work with land and natural resources every day, such as fisherman, farmers and land managers, can and should play important roles in monitoring change and devising local and regional strategies for achieving societal goals. Knowledge that has accumulated over long time periods, such as the traditional ecological knowledge present in contemporary tribal communities, is particularly valuable because it has been progressively adapted and refined across many generations.

Temporally deep traditional ecological knowledge can complement and enhance other type of knowledge and tools used in the face of environmental change. In managing their lands and resources, tribal communities leverage their geographically-specific TEK along with Western science to make decisions on a daily basis. They rely upon their TEK in concert with Western scientific information internally and in their resource management partnerships. For example, Lynn and colleagues (2013) describe how the Confederated Tribes of the Umatilla Reservation is protecting its traditional, wild gathered foods by leveraging multiple sources of knowledge through a Tribal-federal resource management partnership.

Today we have access to data and knowledge at a global scale, something unavailable in colonial or pre-colonial New England. Contemporary scientists and decision-makers can leverage global climate and carbon models and have the computational power to forecast environmental changes given a wide range of temporal and spatial scales and scenarios. This nearly instantaneous, cheap, contextualized information is useful for devising adaptation and mitigation strategies and testing their efficacy through modeling, simulation and adaptive management. Such global-scale, rapidly available knowledge forms a foundation for enacting negative feedback loops. An important area of work involves linking the forecasting and simulation powers of modeling approaches with deeply contextualized local and traditional ecological knowledge held by resource practitioners such as farmers, commercial fisherman and subsistence harvesters (e.g., Kruse et al. 2004).

5 Conclusions

In this paper, we demonstrated a line of research that studies colonial history to gain insights for responding to rapid environmental change. The fact that we were able to illuminate key feedbacks and reciprocal human-environment interactions, despite our relatively brief analysis, highlights the potential this methodology holds for researchers and practitioners working to understand the dynamics of environmental change. Future scholarship in this same vein could inform adaptation and mitigation projects undertaken by resource practitioners, policy makers and communities. With this potential in mind, we have a few suggestions for how to approach future research.

As Butzer and Endfield have pointed out, “The challenge remains to develop an outline for comprehensive, integrated models that convincingly explicate past socio-ecological interactions, or that capture the broader, dynamic principles crosscutting human–environmental systems while also accounting for the finer resolution evidence and complex outcomes that they entail” (2012). Researchers can simultaneously accomplish both of these goals through an interdisciplinary approach such as the one modeled in this essay. In doing so, ecologists and environmental scientists benefit from seeing their conceptual frameworks populated with the complexities of historical examples. On the other hand, historians benefit from using the conceptual tools developed in ecology as a way to organize the analysis of complex historical information. In our example, we studied colonial New England through the lens of coupled natural human systems, focusing on reciprocal feedback loops between human and natural systems and tipping points that transition systems into distinct states. This conceptual framing was fruitful; future historical research should leverage these and other concepts, including legacy effects (Moon and Stiling 2003; Liu et al. 2007) and domino effects (van Nes and Scheffer 2005; Dejong 2009) in coupled systems. Perhaps most important are detailed studies of social, cultural and political adaptations among indigenous and colonist groups in the wake of colonialism. We did not look at adaptation specifically because our nascent analysis relied solely on secondary sources, and very little historical research explores the socio-cultural adjustments made by indigenous groups of New England directly following colonization. Endfield (2012) provides an important example of how primary source research can illuminate a nuanced understanding of societal features that built adaptive capacity and resilience in colonial era Mexico. Future work following a similar path could lead to important insights for contemporary communities (indigenous and non-indigenous) both in and outside of the U.S. as they face the challenges of a changing climate (see, for example, Endfield 2012; Harris 2012). While this Special Issue of *Climatic Change* focuses on tribal communities in the U.S., our recommendations for future research are applicable in any location where colonialism transformed coupled human and natural systems, i.e., globally.

Acknowledgments This paper benefited greatly from generous reviews by Ross Virginia, Colon Calloway, Emily Blackmer, Benedict Colombi, Julie Moldanado and four anonymous reviewers.

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