Ready-to-use? - Bridging the climate science-usability gap for adaptation

By

Kripa Akila Jagannathan

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy
in
Energy and Resources
in the
Graduate Division
of the
University of California, Berkeley

Committee in charge:

Professor Margaret Torn, Co-Chair
Professor Isha Ray, Co-Chair
Professor Alastair Iles
Research Scientist Andrew Jones

Spring 2019

Ready-to-use? - Bridging the climate science-usability gap for adaptation

Abstract

Ready-to-use? - Bridging the climate science-usability gap for adaptation

by

Kripa Akila Jagannathan

Doctor of Philosophy in Energy and Resources

University of California, Berkeley

Professor Margaret Torn, Co-Chair

Professor Isha Ray, Co-Chair

As societies across the world increasingly experience the devastating impacts of climate change, there is an urgent need to implement and accelerate adaptation actions. Effective adaptation decisions need to be grounded in, and supported by robust science on expected climate change and its impacts. Despite several advances in climate science and modeling, the use of science in adaptation decisions is still very limited. This suggests that there is a gap between the production of climate science, and its use in adaptation i.e. there exists a climate science-usability gap for adaptation. My dissertation deconstructs the various aspects of this gap, by identifying the types of scientific knowledge and the processes of knowledge production that can lead to increased uptake of climate information in adaptation decisions. The overall aim of my research is to bridge the usability gap, by providing scientists with a better understanding of decision-makers' climate information needs, providing decision-makers with an improved understanding of how science may be useful in their adaptation contexts, and recommending broader systemic changes that can sustain the development of usable science. Finally, this dissertation argues for and promotes 'engaged' models of research, where scientists and decision-makers jointly develop climate science that achieves more benefit to society.

Chapter 1 of this dissertation reviews on-the-ground adaptation projects from across the world to understand how adaptation is conceptualized and promoted by the international community, and the types of scientific information that are used in the planning and design of these projects. Using the case of ecosystems-based adaptation, we find that 65% of adaptation projects either did not use any information on expected climate change, or just used broad macro-scale climate projections that were not specific to local sectoral contexts. A majority of projects did not address uncertainty in future climate change or in adaptation benefits, nor did they track adaptation outcomes. This pervasive lack of use of climate science to inform adaptation actions is concerning, as it is difficult to ascertain the level of climate impacts that these adaptation projects can cope with.

Chapters 2.1 and 2.2 identify decision-makers' climate information needs for undertaking adaptation action. Through semi-structured, exploratory interviews with perennial tree crop growers in California, Chapter 2.1 finds that farmers perceive long-term climate projections as an extension of weather forecasts, which can often lead to their skepticism of the utility of such information. Hence, the manner in which long-term projections are framed, presented, and discussed with farmers is critical to how they may perceive the potential utility of such information. We find that in-depth iterative conversations were essential to effectively understand the types of climate projections that are useful to farmers, and recognize that projections of crop-specific agro-climatic metrics are often more useful to farmers than projections of physical climatic metrics. Such conversations help in joint construction of meaning, or in this case joint understanding of useful climate information, where the farmer and the interviewer both improvise and iterate to find the best types of projections that fit specific decision-contexts.

Chapter 2.2 presents a case of co-production (Project Hyperion) wherein scientists and water managers jointly developed decision-relevant metrics for adaptive water management. We find that arriving at these actionable metrics is more complicated and iterative than is generally acknowledged in the literature. We identify engagement strategies that target both direct and indirect knowledge elicitation as effective approaches for translating managers' needs into quantitative metrics. These strategies, along with the list of metrics we develop, provide tangible recommendations to both researchers and practitioners seeking to develop usable climate information.

Chapter 3 evaluates the skill of different Global Circulation Models (GCMs) in predicting decision-relevant climatic metrics (using the case of chill hours in California), and examines how differences in model choice may impact future projections. We find that the multi-model mean of GCMs is not the best predictor of this specific metric. Additionally, downscaled LOCA projections, which is a dataset recommended by the State of California, systematically underestimate the negative trend observed in historical chill hours. Further, we also find that good skill in predicting broader physical climate metrics does not guarantee skill in prediction of specific decision-relevant metrics such as chill hours. Since many decision-relevant metrics are non-linear derivations of primary physical quantities, approaching model evaluations through the lens of decision-relevant metrics can provide critical insights on model choice for adaptation decisions.

Finally, Chapter 4 reviews recent co-produced climate change adaptation projects alongside the theoretical scholarship about co-production – to compare the expected theoretical outcomes of co-production with those that are reported in practice. In bringing these two streams of thought and action together, we find that the practice of knowledge co-production is realizing improvements in knowledge utilization, but is not reporting on the more radical or transformational outcomes that the theory expects from co-production (such as changing power dynamics, transforming dominant knowledge paradigms and bringing institutional change). We identify five key reasons for why co-production practice may be falling short of its expectations. We propose that to address these issues and unleash the full potential of co-production, a more transparent, conversant, and interactive research agenda and discourse is required.

Table of Contents

ACKNOWLEDGEMENTS

I consider my dissertation to be not just my achievement but also a collective effort. And true to my Indian self, I am going to try and thank the entire city (or cities) of people that enabled this achievement. I would first like to thank my parents, my sister, and my husband who have been pillars of strengths and my 'constants' during this journey. I have not always seen eye-to-eye with my parents or even my sister, but their constancy through all of the disagreements is one of the main reasons I was able to take the bold step of pursuing my dreams, and work through all the obstacles in its path. The courage that they have shown in their lives is an example that I try and live by. And there is nothing that I can say in words that even begins to explain the support, love, and drive that Swarup infuses me with everyday. Despite everything that we were dealing with, my dreams were always his priority, even if it was occasionally at his cost. Whether it was the long-work days with no time at home, or long travels without seeing him for a while, he has NEVER ONCE made me feel like I was not present. Thank you Swarup for making it all just so easy!

My family and friends back home in India have been an equal part of this journey. Swarup's family has always backed my passion to study further, in fact the first question that my mother-in-law asks every time she calls me is "how are your studies going?". My extended family has stepped up to support not just me, but also my parents and sister when I was too far away, and for that I will forever be grateful. And no matter how far away I am from my closest friends – Sairam, Astha, J, Neha, Anjan, Moumita, my PwC kiddos, my TERI gang, my GFS gang – they all have treated me just the same as before.

My rockstar dissertation committee have helped transform me into the researcher and the person that I am today. Margaret is one of the most positive, warm, and truly caring people that I have ever met. And her genuine interest and passion to support ERG students is infectious. She was the first faculty member that agreed to be in my committee, even though our topical interests did not match-up straightforwardly. Margaret, for all the love and affection you have showered on me, and for asking the most difficult 'simple' questions and making me a critical scholar – Thank you! I am pretty sure, I pestered and annoyed my way into being Isha's student. Ever since I heard her give a colloquium talk at the end of my first semester at ERG, I had decided that I wanted her as an advisor. I approached her without having taken a single social sciences course in my life, and through my keen observation of the ways she thinks, her dedicated guidance and brainstorming sessions with me, I think I can call myself a social scientist now. When Isha decides you are her student, she is in your corner forever. So thanks Isha for being such a role model, and for all of you support and encouragement. I met Andy at LBL for what was supposed to be a very short exploratory data analysis. But we quickly realized that we were 'kindred research spirits' in wanting to work on making climate science more actionable. Almost five years since, we have collaborated on some amazing projects and are even at a place where we often finish each other's sentences. Whenever Andy has presented our work in public fora, he not only acknowledges my contribution openly, but also makes me feel like a superstar, which is just one of the wonderful characteristics of this overall amazing person. So thank you Andy for giving me my

‘Beyonce’ moments in life, I cannot wait to work on more projects with you. Alastair was the last member to join my committee, and it was about 3 years into my time at ERG. But it only took Alastair 30 minutes to not just understand my research objectives and projects, but also determine the kind of researcher I am and want to be. Sometimes I feel like within two lines into my answer to his question, he already knows what I am about to say – and it is the most amazing feeling to have an advisor who knows and understands me so well. In each of his meetings with me, he has patiently listened to all my thoughts and helped frame my work in a better, more critical manner. So thank you Alastair for your time, dedication, and your commitment to helping me.

My newbies2013 cohort, have been my family away from home! Laura, Nikky, Chris, Vero, Madison (adopted ERGie), Andie, Julia (adopted 2013newbie), Noah, AP, Susty, Pete – thank you all so much. You all got me here – and I am at a loss for words to describe how I feel about all of you!!! My other ERGie support systems include the most special Zach, Sharada, Ranjit, Grace and Danielle – they have been friends, mentors, confidantes, travel mates, and in general the most loving group of friends I could ask for. Some of my most treasured memories from ERG are Zach and Ranjit visiting my parents in Delhi (when I was not around), and Sharada letting me know that he will be my friend only until I continue to make him mor kozhambu (Indian yogurt, coconut and green chilli based yummy curry). And to my countless other ERGie friends – Cecilia, Laney, Jess G, Pierce, Yoshika, Emma (just to name a few), the Water+ Group, and my LBL friends – thank you for being such inspirations and showering me all the love and support.

I would DEFINITELY not be here without Kay, she has always listened to every problem no matter how small or insignificant. Thank you Kay for being my Berkeley mom! She and Megan work so hard to keep ERG functioning smoothly and that dedication is what makes ERG the department that it is. Thanks also to the ERG faculty - Dan, Duncan, David, John and Lara - whose encouragement, support and critique of my work at the different classes and seminars, have been invaluable. It is not often that one is in the presence of so many leaders and transformative thinkers, and I hope that some of it has rubbed off on me.

None of my projects would have materialized without the support of my collaborators. Starting with Anita Milman, Amber Kerr, Tapan Pathak, David Doll, the almond farmers and farm advisors who I interviewed, the Hyperion project team, and the SESYNC co-production working group (particularly James Arnott and Maria Lemos), every one of these individuals have shaped and molded the way I think and I am immensely grateful to have had the opportunity to work with such a stellar group of people.

And finally, no dissertation is accomplished without financial support. I would like to thank ERG, LBL (especially Peter Nico and Project Hyperion), USDA California Climate Hub, UC President’s Global Food Initiative Fellowship & Carbon Neutrality Initiative Fellowship, Annie’s Sustainable Agriculture Scholarship, UC Division of Agriculture and Natural Resources’ Graduate Student in Extension Fellowship, and the Philomathia Graduate Fellowship in Environmental Sciences.

Thank you all for making my Berkeley dream come true!!

INTRODUCTION

THE CLIMATE SCIENCE-USABILITY GAP FOR ADAPTATION

From the raging wildfires in California and the devastating floods in Texas, to the deadly heat waves in southern India and the intense droughts in East Africa, societies worldwide are already experiencing the destructive impacts of climate change (Adger et al., 2005; Noble et al., 2014). Both human and natural systems are contending with warming temperatures, alterations to the hydrologic cycle, sea level rise, and an increased frequency and intensity of extreme events (IPCC, 2014). The mounting recognition that current and expected mitigation efforts will not prevent these negative impacts, has made adaptation[1] to climate change an inevitable necessity (Mimura et al., 2014; Mullan et al., 2013; Pielke et al., 2007). There is now an increased urgency to design and implement adaptation measures that can effectively combat the effects of climate change.

One of the key elements of successful adaptation planning is the use of climate knowledge and robust science to inform adaptation action and policies (Dilling and Lemos, 2011; Tang and Dessai, 2012). Adaptation solutions need to be grounded in, and supported by scientific information on climate change (Kirchhoff et al., 2013a; Klein R.J.T. et al., 2014; Lemos et al., 2012). Recognizing the urgency and need for such science-based adaptation, decision-makers[2] are actively demanding climate science that can support adaptation decisions (Mcnie et al., 2013; National Research Council, 2009; Vaughan et al., 2018). Resource managers, land planners, as well as agricultural stakeholders are increasingly looking for support from the scientific community to better understand expected future climatic changes, sectoral impacts, and coping strategies that can aid in effective adaptation planning. At the same time, several advances have been made in climate science and modeling which has led to an improved understanding of regional- and local-level climate change and its impacts (IPCC, 2013a). Despite both a demand for and an apparent increase in supply and quality of climate science, the use of climate information in adaptation plans, policies, and decisions, is still very limited (McNie, 2007). This indicates that there is a mismatch between current climate research outputs and decision-makers' climate information needs. This mismatch has largely been attributed to the lack of 'usability' of climate science (and the knowledge produced from the science) for making adaptation decisions (Kirchhoff et al., 2013a; Lemos et al., 2012; Tang and Dessai, 2012).

DEFINING USABILITY

Usable science refers to science that contributes directly to the design of a policy or a solution to a problem (Dilling and Lemos, 2011). More specifically, usability can be defined as a function of users' *perception of usefulness* of science and their *actual capacity* to use the knowledge in decision-making (Dilling and Lemos, 2011). Users' *perception of usefulness* further depends on their perception of credibility, salience, and

---

[1] Adaptation refers to the process of adjustment to actual or expected climate and its effects (Noble et al., 2014).

[2] For the purposes of this dissertation, the term 'decision-maker' refers to the broad set of adaptation practitioners or policy-makers including farmers, farm advisors, resource managers or land planners all of whom could potentially be making adaptation decisions in their sectoral contexts.

legitimacy of the science (Cash et al., 2003). Cash et al (2003), define credibility as the scientific adequacy of knowledge, salience as the relevance of the knowledge to decision-making needs, and legitimacy as the perception that the production of science has been respectful, unbiased, and fair in treating stakeholders' divergent values and beliefs. On the other hand, *actual capacity* can refer to human and financial resources, institutional and organization support, political opportunity, and other such capabilities that impact the ability of users to take action based on the knowledge. Lemos and Morehouse (2005) summarize usable science as that which "reflects expressed constituent needs, is understandable to users, available at the times and places it is needed, and accessible through the media available to the user community". Drawing on these concepts, in my dissertation, I focus on three key elements of climate science usability: the type of scientific knowledge produced; the process of knowledge production; and the translation and communication of research results and processes (Figure 1).

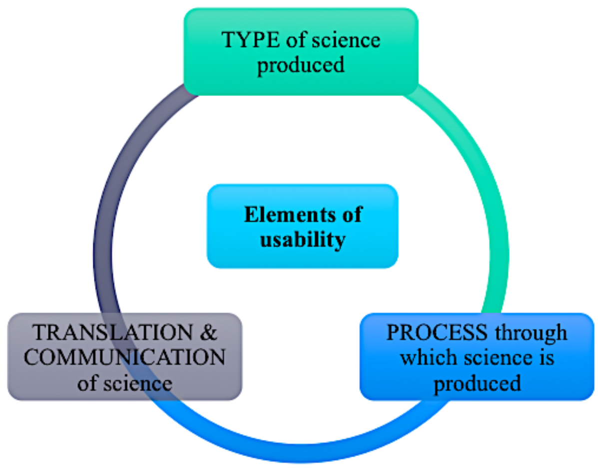

Figure 1: The three elements of usability of science that this dissertation focuses on.

'ENGAGED RESEARCH' FOR IMPROVING THE USABILITY OF SCIENCE

The necessity for, and barriers to, production of usable climate science has been increasingly recognized and acknowledged in the last couple of decades. Yet, only limited progress has been made in effectively addressing this necessity. One of the primary reasons for this limited progress has been that there is a mismatch between what scientists[3] understand as useful science and what decision-makers recognize as usable in their context (Dilling and Lemos, 2011; Lemos et al., 2012). Scientists do not always fully understand decision-making processes and contexts, and on the other hand decision-makers may not know or may have unrealistic expectations of how science fits in their decision-making (Lemos et al., 2012). For example, Kirchhoff et al 2013a suggest that the scale of assessment that climate science focuses on, does not always match the scale required for a potential adaptation response, as scientists may not be aware of management and decision scales. On the other hand, decision-makers may not know what scientists have to offer in terms of uncertainty and reliability of scientific results,

[3] In this dissertation, I use the terms scientist or researchers more broadly to encompass natural, physical, social, interdisciplinary and other scientists or researchers working on climate change and related issues. I also use the terms scientists and researchers interchangeably.

limitations of the science, as well as the potential choices, trade-offs and risks in using that information in decision making (Kirchhoff et al., 2013a). In order to bridge the usability gap and better connect scientific knowledge with adaptation decisions, many scholars have called for a new relationship between science and society (Gibbons, 1999). This scholarship promotes 'engaged research' models that focus on research processes actively engaging with users of science to develop context-specific and user-relevant research (Fortmann, 2008; Gibbons, 2000; Gibbons et al., 1995; Latour, 1998). There is increasing evidence that meaningful interactions between researchers and users of research will generate more accessible, relevant, credible and usable[4] knowledge, thus increasing the likelihood of its use in practice (Lemos et al., 2018; Lemos and Morehouse, 2005; McNie, 2008; Tall et al., 2014; Vogel et al., 2016).

In the realm of climate change adaptation science, one such engaged research model termed as 'co-production', is becoming a widely accepted best practice for those aiming to (co-) generate actionable or usable climate science (Beier et al., 2017; Lemos et al., 2018; Lemos and Morehouse, 2005). Co-production (for the purpose of my dissertation) refers to a process where scientists and decision-makers jointly engage in the development of scientific knowledge. In such processes, the research is shaped in an ongoing iterative manner between scientists and information users, thereby creating knowledge that better fits users' needs (Dilling and Lemos, 2011; Lemos and Morehouse, 2005). Users are engaged at all stages including formulating the problem and research questions, selecting methods, generating data, analyzing findings, and disseminating results. If co-production is done well, it can produce sustained interactions and relationships among participants, which in turn can build trust. This can lead to changes in both the groups' perceptions of each others needs, and in the usefulness and value of the knowledge created (Lemos and Morehouse, 2005). By drawing on the unique experiences, expertise, needs, and limitations of users, co-production provides a strong underpinning for adaptive action by society (Vogel et al., 2016, 2015).

The aspirations of co-production are not limited to development of actionable knowledge, but include much loftier ambitions of enabling a new 'social contract' for science. In this new contract, science is more socially accountable, reflexive, and is inclusive of a much broader range of expertise and perspectives (Gibbons, 2000, 1999; Latour, 1998). In this manner, co-production is expected to democratize science; to broaden the scope and meaning of evidence in decision-making; and to eventually redistribute power and expertise among different groups within society (Klenk et al., 2017).

OVERALL AIM OF THIS DISSERTATION

The overall aim of my dissertation is to bridge the climate science-usability gap, by identifying the types of scientific knowledge and the processes of knowledge production that lead to an increased uptake of climate information in adaptation and that can promote new science-society relationships. I do this by engaging with both climate science and adaptation decision-making (and by corollary with both scientists and decision-makers). Through this work, I provide scientists with a better understanding of decision-makers'

[4] In this dissertation (and in a lot of the literature) the term 'usable' science is used synonymously with the terms 'decision-relevant' and 'actionable' science.

climate information needs, provide decision-makers with an improved understanding of how science may be useful in their adaptation contexts, and finally recommend systemic changes that can further promote these new science-society relationships. My dissertation takes an 'engaged research' approach wherein interaction with decision-makers (either through interviews, focus-group discussions, or co-production) forms a core part of my work, and these engagements inform and influence all of my research. Further, my research also critically investigates the theory and practice of co-production, to provide recommendations on how co-production efforts can further benefit society. I focus on adaptation in several sectors including agriculture and water resources management, with some of my projects cutting across different sectors, and others focusing on a single one. Specifically, my dissertation answers four research questions (Figure 2), which are presented in this document as four chapters. In the subsequent parts of this introduction, I introduce these questions with a brief background and rationale on how they fit under my overarching research aims.

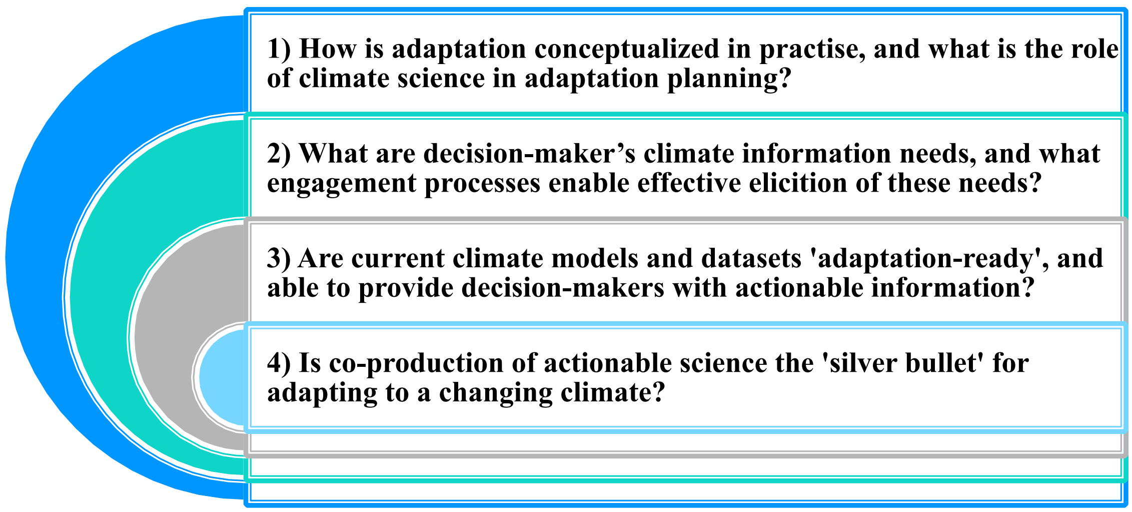

Figure 2: Research questions that the four dissertation chapters address.

INTERPRETING 'ADAPTATION' AND EXAMINING THE ROLE OF CLIMATE SCIENCE IN ADAPTATION PRACTICE

The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as the "process of adjustment to actual or expected climate and its effects" (Noble et al., 2014). As this definition is broad, the scope of measures that constitute adaptive actions is also broad and subject to interpretation (Biesbroek et al., 2013; Dupuis and Biesbroek, 2013; Noble et al., 2014; Stadelmann et al., 2015). The IPCC reports that "adaptation and development specialists, governments, NGOs, and international agencies have found it difficult to clearly define and identify precisely what constitutes adaptation" (Noble et al., 2014). Specifically, questions arise regarding the temporal timeframe of the climatic conditions being responded to, as well as the linkages between adaptation to climate change and other development and environmental goals.

Adaptation can be interpreted as only those actions that directly intend to address climate change, or as inclusive of actions that are motivated by other environmental, development, and risk management concerns which also provide adaptation benefits (Ayers and Dodman, 2010; Khan and Roberts, 2013; Mcgray et al., 2007). Therefore, depending on the interpretation, adaptation can either target a specific climatic hazard or the underlying factors that cause a climatic hazard to have a negative impact. Additionally, adaptation can target future changes in climate or it can target current climate adaptation deficits (Dupuis and Biesbroek, 2013; Smit and Wandel, 2006). Each of these targets and interpretations reflect a differing perspective on the scope and boundaries of adaptation. This differing interpretation is important as the way in which adaptation is conceptualized by practitioners, can determine the role and importance of climate science in adaptation decision-making (Dessai et al., 2009; Lu, 2009).

In addition to the interpretation of adaptation, there is limited understanding about the informational requirements for adaptation decision-making. Irrespective of how adaptation is conceptualized, identifying, designing, and implementing adaptive actions will require some amount of information on expected changes in climate, sectoral impacts, adaptation needs, and performance of adaptation activities (Dessai et al., 2005; Klein R.J.T. et al., 2014; Mcgray et al., 2007). Some authors suggest that broad discussions of climate change may be sufficient for adaptation efforts focused on reduction of underlying factors causing vulnerability of systems (Lu, 2009). Here, precise climate predictions are not always most critical; instead other broader sectoral information become more important drivers of decisions (Lu, 2009; Mcgray et al., 2007). On the other hand, a climate-centric project such as designing of a coastal defense infrastructure may need specific local-scale wave and surge height information along with sea level rise projections. This indicates that need for information likely varies considerably with adaptation conceptualization as manifested in the practitioners' primary objectives, spatial and temporal scales, and planning horizons (Lu, 2009).

Chapter 1 of my dissertation undertakes an examination of on-the-ground adaptation projects around the world, to provide a better understanding of how adaptation is being defined and implemented in practice, and the potential implications of these framings. I also examine the scientific information used by adaptation projects to shed light on the type, complexity, and certainty of information necessary for undertaking adaptation efforts. Such an analysis can help guide the production of knowledge that is both useful and useable (Dilling et al., 2014).

DECISION-MAKERS' CLIMATE INFORMATION NEEDS AND PROCESSES THAT ENABLE ELICITATION OF THESE NEEDS

Several scholars have suggested that the progressing ability to predict future climate, could potentially hold immense value for climate-sensitive sectors such as agriculture and water management (Hansen, 2002; Mase and Prokopy, 2013). However, current climate-modelling efforts typically provide information on larger scale physical climate phenomena of climatological or meteorological relevance (e.g. large-scale atmospheric patterns and averages/extremes in temperature and precipitation), which are not always considered actionable by decision-makers (Briley et al., 2015; Mote et al., 2011; Roncoli et al., 2009). Decision makers' climate information needs often depend on their local sectoral context and their specific decision-making contexts. For example some farmers may require information about start of rains during the planting season or number of low temperature days during the growing season, while some water managers may need information about the frequency and intensity of specific rainfall events (Briley et al., 2015; Mote et al., 2011; Roncoli et al., 2009). However, few studies have systematically identified what decision-makers consider to be decision-relevant climatic information for sectoral adaptations (Hackenbruch et al., 2017; Vano et al., 2019). There is limited knowledge about the specific climatic metrics for which climate projections are required, the spatial and temporal scales of relevance, and decision-makers' thresholds for uncertainty in information.

A growing body of literature suggests that an increase in interactions between climate researchers and information users contributes to development of more usable science and hence a greater understanding, acceptance, and uptake of science in decision-making (Dilling and Lemos, 2011; Lemos et al., 2012; Reed, 2008). Some researchers argue that the first step towards improving efforts to increase uptake of climate information, should be an 'exploratory phase' where researchers gain an understanding of the users' decision-context, their potential to benefit from climate projections, and the types of information that would benefit their contexts (Hansen, 2002; Ortiz, 1980). Particularly, Hansen (2002) suggests that researchers first need to understand decision-makers' institutional context, decision options, vulnerabilities, opportunities to reduce vulnerability using climate information, level of knowledge of climate information, preferred information communicators, and their flexibility to modify decisions based on future projections.

To sustain this production of usable science and maintain trust between scientists and decision-makers, regular interactions and partnerships are required (Bartels et al., 2013; Briley et al., 2015). Therefore, in addition to exploratory interactions with users, the science usability literature also focuses on 'co-production' of climate knowledge as a means to sustainably bridge the gap between climate information and its use (Dilling and Lemos, 2011; Lemos and Morehouse, 2005). Co-production involves forming collaborative partnerships between knowledge producers and users who actively conceive, enact, and apply research by leveraging expertise from all parties (Briley et al., 2015; Klenk et al., 2015). In summary, literature on actionable climate knowledge suggests that engaging in exploratory interactions with potential users of climate information to understand their decision-contexts, and co-producing climate knowledge with such users can help reduce the gap between climate science and its use in adaptation.

Despite its promise, both the co-production and the interactive exploratory research literature suggest that not all interactions or engagements with decision-makers are equally effective or even beneficial (Klenk et al., 2017; Lemos et al., 2018; Porter and Dessai, 2017). Hence there is a need to focus on the level and quality of interactions between scientists and users, and to identify the engagement processes that are able to better elicit user needs and expertise (Lemos et al., 2012; Porter and Dessai, 2017). Keeping this complex context in mind, Chapter 2 focuses on engaging with decision-makers to understand how they might use projections of future climate, while making adaptive decisions. In this chapter I not only aim to identify the types of knowledge that decision-makers consider usable, but also to identify the engagement processes that are able to effectively elicit decision-makers' information needs. In Chapter 2.1, I conduct exploratory interviews with farmers and farm advisors to understand how long-term information can be useful for their decision-contexts. In Chapter 2.2 I undertake and examine a co-production project wherein scientists and water managers jointly develop usable climate science for adaptation.

Adaptation 'readiness' of climate models and datasets

According to the IPCC's Fifth Assessment Report, capabilities to model climatic processes and future climate change have been improving steadily in the past decade. Several climate models now cover representations of biogeochemical cycles, including an interactive carbon cycle, which are important for climate change simulations. These models are also skilled in simulating many aspects of surface temperature both at global and regional levels. Modeling of precipitation patterns has improved considerably though it does not perform as well as surface temperature simulations (Flato et al., 2013). However, current climate models were primarily developed for providing a better understanding of global climatic processes and guiding policy-makers on mitigation strategies (Nissan et al., 2019), and not for providing adaptation relevant information (Kundzewicz and Stakhiv, 2010). Hence, modeling outputs often provide information on broad metrics of climatological relevance, and do not always provide information on the specific actionable climatic metrics that are most relevant to adaptation.

A small subset of the information on climatological metrics can potentially be useful for adaptation. However, Barsugli et al (2013) suggest that decision-makers face an additional challenge regarding how to choose an appropriate data set, assess its credibility, and use it wisely in their adaptation contexts. Currently, there are over 60 different climate models providing a range of results, and the burden is often on the user-community to reconcile these disparate results (Kundzewicz and Stakhiv, 2010). Sorting through these many datasets is challenging even for scientists, and there are not many systematic evaluation frameworks to assist in the choice of the most appropriate models/datasets (Barsugli et al., 2013). The lack of actionable climate projections and the lack of guidance on choosing the most appropriate climate models, are two critical scientific limitations that impact usability of climate information.

Evaluating climate predictions against observations (i.e. skill evaluations) can be a strategy to identify the most appropriate climate models for a regional adaptation context (CCTAG, 2015; Hawkins and Sutton, 2009). Some such evaluations have been conducted as part of various global or regional assessments of climate models; however, these analyses focus on broader climatic metrics such as average annual surface temperature, and not the context-specific metrics that are relevant for adaptation planning. Hence, there is an increased need for climate model performance evaluations focusing on decision-relevant metrics which are also accessible to both practitioners and scientists (Kundzewicz and Stakhiv, 2010; McSweeney et al., 2012; Moss et al., 2019). These decision-relevant evaluations can not only inform the credibility of climate models in providing actionable information, but can also provide guidance on selection of models and datasets for adaptation decisions (CCTAG, 2015; McSweeney et al., 2014, 2012).

Chapter 3 of my dissertation conducts one such decision-relevant climate model performance evaluation, and examines how well various climate models are able to predict the decision-relevant metric of chill hours in California agriculture. Based on the evaluation, this chapter also provides practitioners (including farmers and farm advisors) with guidance on choosing the most appropriate models and datasets for their specific adaptation contexts.

CO-PRODUCTION: THE 'SILVER BULLET' FOR IMPROVING USABILITY OF SCIENCE?

While the earlier sections strongly suggest that increased engagement with users can improve the production and use of decision-relevant science, a question still remains as to whether simply bringing together scientists and practitioners is enough for this mammoth task. Engaging users and co-producing climate knowledge is not without problems. Such processes require heavy investments in time and resources, and transcending disciplinary and epistemological boundaries, and hence face barriers of conflicting values, theories, and assumptions (Gibbons, 2000; Kirchhoff et al., 2013a; Klenk et al., 2015; Vogel et al., 2016). Balancing these divergent viewpoints and expectations can present challenges that may not have easy resolutions, and there may be immutable limitations to producing decision-relevant science (Briley et al., 2015; Lemos and Rood, 2010; Vogel et al., 2016). Ensuring accountability and long-term sustainability of co-production efforts can also be difficult (Briley et al., 2015; Klenk et al., 2015). In addition, there are not many assessment frameworks for analyzing the actual outcomes achieved from co-production projects, or to identify good practices and enable social learning (Hegger et al., 2012).

Although the co-production approach has gained popularity in the climate adaptation research space, recent literature indicates that not all co-production leads to desirable outcomes, and there may be un-intended negative consequences from such interactions (Klenk et al., 2017; Lemos et al., 2018; Porter and Dessai, 2017). In-depth studies focusing on different decision contexts point to ways in which co-production may marginalize communities and ideas, and limit the scope of decisions and research foci (Klenk et al., 2017; Lövbrand, 2011; Meehan et al., 2017). These studies suggest that depending on how the co-production is framed and conducted, it could reinforce existing power dynamics or limit scientists' ability to consider alternative lines of action that challenge and transform current decision-making agendas. Tracking the experiences and results from actual co-production projects, would foster better understanding of when and how co-production is beneficial, and what strategies can be scaled up to increase its impact (Lemos et al., 2018). However, there have been very few systematic evaluations of co-production projects and their outcomes. Hence the actual benefits achieved from co-production remain largely speculative.

The last chapter of my dissertation, Chapter 4, conducts an analysis of recent co-production projects (focusing on generating actionable science for adaptation), to compare the idealized theoretical co-production outcomes with the actual outcomes reported by these on-the-ground efforts. Such an analysis can help provide a more realistic perspective of the benefits that co-production is currently achieving, and identify potential areas of improvement for the co-production practice.

Finally, I conclude with a short essay on how we can effectively and sustainably continue to generate usable science that enables societies around the world to combat this beast of a challenge that is climate change.

CHAPTER 1

1. CONCEPTUALIZING ADAPTATION IN PRACTICE AND THE ROLE OF CLIMATE SCIENCE

This chapter examines how practitioners across the world conceptualize adaptation, and the types of scientific information used in these adaptation efforts. The in-depth content analysis of over 40 adaptation projects provides a better understanding of the types and extent of current adaptation activities. It also sheds light on the role that climate science plays in current adaptation projects, and how practitioners' are addressing uncertainties in climate information. This chapter was published in the journal 'Climatic Change' in 2017, and is included in this dissertation with the permission of my co-author - Dr. Anita Milman. The both of us designed the research, collected project reports that form the data for the paper, undertook the content analysis of the reports, analyzed and coded the reports, and wrote and edited the manuscript.

1.1.1 *INTRODUCTION*

The impacts of anthropogenic climate change are already being experienced. Human and natural systems are contending with warming temperatures, alterations to the hydrologic cycle, sea level rise, and an increased frequency and intensity of extreme events (IPCC, 2014). Recognition that current and expected mitigation efforts will not suffice to prevent negative impacts of anthropogenic climate change has lead to increased attention to adaptation (Mimura et al., 2014), including ecosystems-based adaptation (UNEP, 2012; World Bank, 2009).

Ecosystems-based adaptation (EbA) involves safeguarding or restoring ecosystems as a means of helping human communities respond to the adverse effects of climate change (Jones et al., 2012). An attraction of EbA is that fortifying the supporting, provisioning and regulating services that ecosystems provide can contribute to addressing societal concerns beyond climate adaptation including biodiversity, livelihoods, development, disaster risk reduction, and human health and well-being (Baron et al., 2008; Munroe et al., 2012). Yet, like most efforts at this early stage of adaptation (Biesbroek et al., 2013; Khan and Roberts, 2013; Mimura et al., 2014), EbA's requirements and precise effects under future climate change are unclear (Baron et al., 2008; Doswald et al., 2014; Koch et al., 2009; UNFCCC, 2011). Nonetheless, a number of international organizations are actively promoting EbA (UNEP, 2015).

One way in which EbA is being promoted is via the dissemination of information, including examples of on-the-ground projects. An important source of such examples is a database of EbA projects developed and maintained by the UNFCCC (UNFCCC, 2015). The UNFCCC, which serves as the centerpiece for multilateral action to address climate change, commits its parties to formulate, implement, publish and update adaptation measures, as well as to cooperate on adaptation (Stavins et al., 2015). Through its Nairobi

Work Programme (NWP), the UNFCCC aims to assist countries to "1) improve their understanding and assessment of impacts, vulnerability and adaptation to climate change; and 2) make informed decisions on practical adaptation actions and measures" (UNFCCC, 2012). To do so, the NWP disseminates and fosters knowledge among intergovernmental, non-governmental and civil society organizations; universities; and private sector companies (UNFCCC, 2016). Insights gleaned from the EbA database are likely to be incorporated into the policies and practices of donor agencies, into National Adaptation Plans, and into the design and implementation of adaptation projects around the world.

We analyze this database to understand how adaptation is being conceptualized and implemented in the projects identified by the UNFCCC as examples of EbA. In doing so, we contribute to an emerging literature on EbA. To date, the bulk of scholarly work on EbA has focused on elucidating the potential benefits of ecosystems for adaptation to climate change (Doswald and Osti, 2011; Jones et al., 2012; Munang et al., 2014) or on examining the knowledge base on the use of ecosystems for adaptation (Doswald et al., 2014; Sierra-Correa and Cantera Kintz, 2015). A smaller, though growing, line of inquiry has focused on examining processes for and barriers to mainstreaming – i.e., integrating consideration of EbA into ongoing (non-climate) policies and plans (Chong, 2014; Ojea, 2015; Wamsler, 2015; Wamsler and Pauleit, 2016). Though research has sought to promote use of EbA, it has not sought to improve clarity as to which specific practices and activities constitute EbA. Only one article examines patterns in what constitutes EbA, yet it focuses on the portrayal of EbA in peer-reviewed research papers (Brink et al., 2016). Our research builds on this by providing an examination of on-the-ground projects, and thus sheds light on how EbA is being defined and implemented in practice.

We begin with a review the literature about EbA, identifying ambiguities in the concept and uncertainties surrounding its design and implementation. Next we describe the UNFCCC database on EbA and the analytical framework we use to examine the projects included in it. We then present our analysis of the conceptualizations of EbA reflected by these projects. Subsequently, we describe the information used in the design of the EbA projects and the relationship between the information used and the conceptualization of EbA. We conclude with a discussion of the implications of these findings.

1.1.2 *Conceptualizing Ecosystems-based Adaptation*

Though the importance of ecosystems services has been long recognized, use of the term EbA is relatively recent and a plurality of conceptualizations of EbA exist (Brink et al., 2016; Mercer et al., 2014). While broadly, EbA refers to the harnessing of ecosystem services in order to buffer communities against the adverse effects of climate change, conceptualizations differ in terms of the activities described as EbA, and the targeting of EbA projects (Jones et al., 2012; Munang et al., 2014; Wamsler, 2015).

In describing the activities that constitute EbA, proponents of EbA emphasize different aspects of the approach. Some characterize EbA in opposition to structural or engineering approaches, others describe it as a bottom-up and participatory form of adaptation, and still others portray EbA as a process with flexible management structures that harmonizes across sectors and scales (Brink et al., 2016; Mercer et al., 2014; Munroe et al., 2012;

World Bank, 2009). Specific actions chronicled as EbA range from vulnerability assessments; capacity building; improvements to policy and management practices; and direct implementation of natural resource management or conservation projects (UNFCCC, 2011).

In addition to a lack of consensus regarding what activities constitute EbA, the underlying objectives of EbA are oft conceptualized differently. Broad reviews of adaptation indicate climate has not always been the primary motivation of many activities classified as adaptation (Berrang-Ford et al., 2011; Brink et al., 2016; Noble et al., 2014; Wamsler, 2015). Additionally, some projects not initially labeled as EbA have been reclassified as EbA and some projects labeled as EbA are primarily aimed at conservation, rather then climate change (Brink et al., 2016; Doswald et al., 2014; Doswald and Osti, 2011; Wamsler, 2015). This raises questions about whether EbA includes only projects designed as a direct response to climate change or if it includes projects motivated by other environmental, development, and risk management concerns that also provide (either by intentional design or as a positive side-effect) climate adaptation benefits (Ayers and Dodman, 2010; Khan and Roberts, 2013; Mimura et al., 2014).

Conceptualizations of the targeting of EbA are also ambiguous. Adaptation can occur through a variety of pathways: it can either target a specific climatic hazard or it can target the underlying factors that cause a climatic hazard to have a negative impact on an individual, organization, or community, including that entity's ability to respond or recover from the hazard. Additionally an adaptation can target future changes in climate or it can target current climate adaptation deficits (Dupuis and Biesbroek, 2013; Smit and Wandel, 2006). Each of these targets reflects a differing perspective on the scope and boundaries of EbA.

While adaptation in general is subject to confusion among international actors (Noble et al., 2014), the indistinctness of scope, boundaries, and objectives is pronounced for EbA and has been cited as a barrier to its use (Doswald et al., 2014; Naumann et al., 2013). By analyzing the projects included in the UNFCCC database of EbA, our research contributes greater understanding of the definitions of EbA the UNFCCC is promoting. More precise definitions of what constitutes EbA will facilitate monitoring, evaluation and comparison of EbA projects, tracking of future adaptation needs and accounting for the contributions of new and additional resources for adaptation (Noble et al., 2014).

1.1.3 *Information and Uncertainty for EbA*

Irrespective of how EbA is conceptualized, identifying and designing adaptation requires information on expected changes in climate, sectoral impacts, adaptation needs, and the performance of adaptation activities (Klein R.J.T. et al., 2014). Determining the benefits from EbA also requires information on the actual performance of project activities over the long-term (Stadelmann et al., 2015). While the literature is overwhelmingly positive about EbA, the processes by which EbA provides benefits are complex and uncertain (Perez et al., 2010; UNFCCC, 2011; World Bank, 2009).

This uncertainty extends to the minimum size of an ecosystems-based intervention needed to be effective in addressing climate hazards, the range of climate change conditions the intervention can address, how long the effects the intervention will last, and the relationship between the scale of an effort and its efficacy (Ojea, 2015). For example, a project to remediate increasing temperatures by planting trees suffers from uncertainty about the minimum planting area required for substantial cooling benefits, the number of years until those seedlings mature to the state where they provide these benefits, the trees' lifespan, and the percent reduction in rainfall the trees can withstand. Few experimental or field data studies have been conducted to address such uncertainties in benefits of EbA (Doswald et al., 2014).

Estimates of the likely effects of adaptation over the long term are confounded by uncertainty surrounding EbA, the severity and timing of climate change, and the influence of changes in non-climatic conditions (Clar et al., 2013; Noble et al., 2014). The impacts of climate change and the benefits of adaptation actions will materialize over the long-term, may not be measureable for decades after the adaptation activities are implemented, and may be altered by changes in non-climatic conditions. Monitoring and evaluating adaptation can help reduce this uncertainty and may include measurements of progress in planning or implementation of projects as well as indicators and proxies to measure effectiveness (Ford et al., 2013).

While adaptation can and does occur in face of uncertainty, uncertainty can be a strong impediment to adaptation (Adger et al., 2007; Klein R.J.T. et al., 2014). Uncertainties in climate impacts and in the benefits of adaptation creates policy risks for adaptation actors (Preston et al., 2015). Decision-makers in the USA described these risks as a challenge to implementing adaptation, in part due to stakeholder pressure for information prior to action (Carlson and McCormick, 2015). The need for information likely varies considerably with a project's primary objectives, spatial and temporal scales, and planning horizons. Moreover, willingness to accept uncertainty depends on whether it is uncertainty regarding climate impacts, adaptation benefits, or social and environmental conditions. It also depends on the context in which risks are being borne (Kettle and Dow, 2016). By analyzing the information used in the design and implementation of EbA projects in the UNFCCC's database, our analysis sheds light on information used to move EbA forward and whether this information varies by conceptualization of adaptation. Our analysis also serves as an indirect measure of project funders' tolerance for uncertainty and indicates how such actors are monitoring the effectiveness of EbA and demonstrating adaptation benefits.

1.1.4 *ANALYTIC FRAMEWORK AND METHODOLOGY*

Drawing on the above literature, we developed an analytic framework (depicted in Table 1) and used that framework to examine the projects included in the aforementioned UNFCCC database. The first part of the framework was used to establish how EbA is conceptualized, in terms of its scope, what problems it seeks to address and how it aims to address them. To do so we identified the sectors and activities included in the projects. We then analyzed the targeting of the projects to determine whether the database includes only projects that primarily and explicitly aim to address climate change, or whether it includes projects that primarily seek to address non-climatic goals. We also analyzed whether the projects aim to address current climate adaptation deficits or future climate change. The second part of the framework was used to ascertain the information used in the design and implementation of EbA projects. We identified the specificity of information on expected climate change and the impacts of those changes as well as the information used to determine the benefits of the project. We also analyzed patterns in how EbA is conceptualized and in information used across projects.

How is EbA conceptualized?	**What information is used?**
What sectors and activities are included in the EbA projects? ▪ Geographic locations ▪ Sectors ▪ Project activities What do the EbA projects target? ▪ Primary objective ▪ Focus on current adaptation deficits versus future climate change How does the targeting of adaptation vary by location, sector and project activities? ▪ Comparison of targeting across location, sectors and project activities.	What specificity of climate and adaptation information is used in project design? ▪ Projections of climate change ▪ Assessments of expected climate impacts ▪ Timeframe for climate impacts ▪ Timeframe for adaptation effectiveness ▪ Range of climatic conditions for adaptation effectiveness ▪ Scale of intervention ▪ Acknowledgement of uncertainty What information is used to determine project benefits? ▪ Tracking of progress and outcomes ▪ Potential for maladaptation ▪ Long-term monitoring How does information used vary by the targeting of adaptation? ▪ Comparison of information used across project primary objectives.

Table 1: Analytic Framework for reviewing EbA projects

Our analysis was based on a review of official documentation for each project. For each project, the UNFCCC database contains a one-page description of the project's context, goal and outcomes along with details on entities involved in funding and implementation of the projects. Further details on the projects were obtained from websites of project funders or implementing agencies, and a Google search using the project's title as the search term. If the first 15-20 results of the Google search did not return information on the project, variations on the project title were used as search terms. Detailed project reports, evaluation documents, and other sources of information were located for a majority of the projects.

Analysis of the EbA project documentation followed standard content analysis methods (Stemler, 2001). Documents were first coded using a priori codes representing each of the bulleted topics in the analytic framework (Table 1). This process served to identify which sections of the project documents include information relevant to each component of the analytic framework. An emergent coding process was then employed. For each component of the analytic framework, we developed discrete sub-codes that encompass the full range of variation across all of the projects in the database. For example, through examination of the project documentation describing the motivation and objectives for each of the projects, it became clear that projects could be divided into four categories: either (i) the aim of the project is addressing current climate conditions or combating impacts expected from changes in average climate conditions, such as increased surface temperature, sea level rise, or alterations to the hydrologic cycle; (2) the aim of the project is managing impacts of natural hazards such as floods or fires as the main motivation, yet with little or no consideration of the contributions of climate change to natural hazards; (3) the aim of the project is improving ecosystem or social resilience, such as restoring degraded wetlands, improving food security, or economic development, yet with little or no consideration of the contributions of climate change to ecosystem or social resilience; or (4) the aim of the project is both addressing climate conditions (current or future) and at least one of development, ecosystem resilience, or natural hazards. Consequently, we developed four emergent codes, one for each of the three different primary objectives and one that reflected that in some instances, those objectives overlapped. These codes were named respectively "climate focus," "natural hazard focus," "development/ecosystem focus," and "climate plus other focus." A similar process was used to develop emergent codes for each of the elements in the analytic framework. A detailed explanation of the project coding, the table of the codes assigned to each project, and a bibliography of the project documents is included in Appendix A.

Coding was conducted by one researcher, with random validation by the second researcher. If the documentation for a particular project did not include information for a specific code, that project was omitted from the analysis for that code. Our analysis is strictly based on the information included in official project documentation that were reviewed (project description and accompanying reports) and does not include an examination of the politics surrounding project implementation or an independent evaluation of project outcomes. As the database was developed for the purpose of providing and disseminating information on adaptation on EbA, any project included in the database is deemed reflective of the UNFCCC conceptualization of EbA.

Projects included in database were identified by the UNFCCC through a review of reports, websites, and other knowledge products produced by organizations engaged in the research and implementation of adaptation (UNFCCC, 2011), and also by project implementers who submitted to the database, information on the EbA efforts they undertook (UNFCCC, 2015). As such, the database may not capture EbA undertaken autonomously by individuals or independent small groups. Nonetheless, the projects in the database constitute the examples the UNFCCC is providing for others to examine and follow.

1.1.5 *Results: Conceptualization of Adaptation*

1.1.5.1 Geography, Sectors and Activities of the EbA Projects

As of January 2015, 43 projects were listed in the UNFCCC database of EbA. The projects' locations are shown in Figure 3 and summary of them is included in Figure 4. Projects span a diverse range of countries and sectors with 51% [22 of 43] of projects located in Non-Annex I countries; 26% [11 of 43] of projects located in Annex I countries; and 23% [10 of 43] of projects located in least developed countries (LDC).

While multilateral and bilateral aid agencies are the primary financers for 51% [22 of 43] of the projects, national governments, and NGOs, are involved in implementation of a majority of the projects.

The sectors addressed by the projects were identified via the content analysis based on the project description and a review of project activities. A majority, 84% [36 of 43] of projects, focus on a single sector including agriculture; forest conservation; shoreline, wetlands, and water management projects; biodiversity, fisheries, and marine conservation; and urban planning. A portion, 16% [7 of 43] of projects, aims to address and include activities that span multiple sectors.

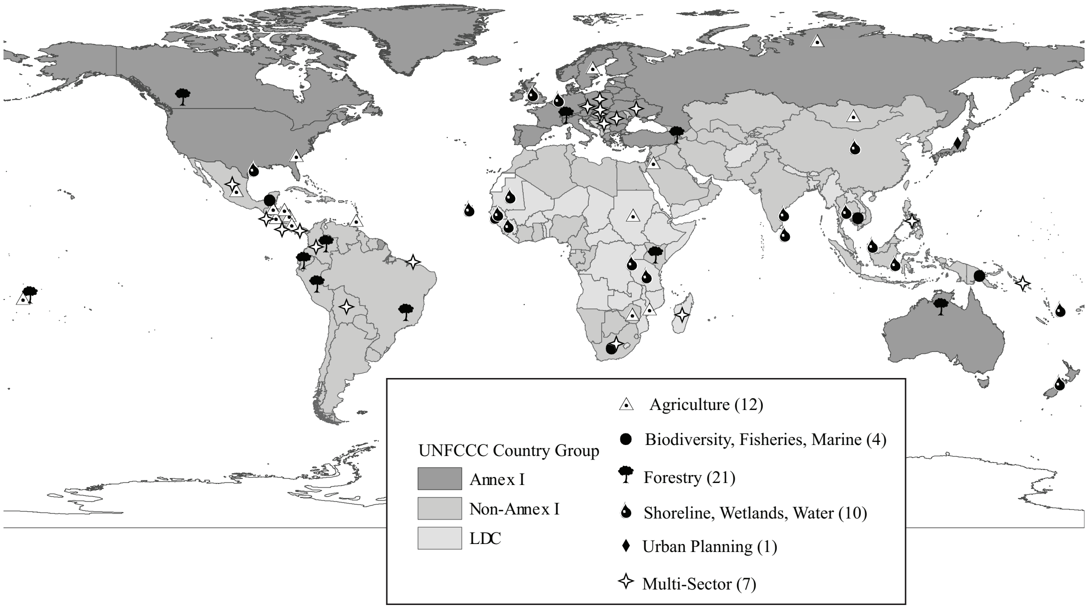

Figure 3: Location of the EbA projects

Project activities undertaken range from planning, to training and assessment, to direct interventions. Most projects undertook more than one type of activity. Forty-five percent [24 of 43] of projects include capacity building activities such as improving communities' awareness of climate change, training farmers, or educating local government officials. Thirty-seven percent [16 of 43] of projects entail climate vulnerability and adaptation assessments for the project region or community while 16% [7 of 43] of projects include the production of new knowledge such as scenario planning tools, collection of scientific data, or creating climate vulnerability maps. Mainstreaming climate change into development and planning formed a part of 28% [12 of 43] of the projects. In terms of actions, 35% [15 of 43] of projects undertook pilot activities designed to be trials or demonstrations and 58% [25 of 43] of projects undertook full-scale implementation of interventions. Fifty-six percent [24 of 43] of projects included development of laws, regulations or policies while 53% [23 of 43] of projects involved creation of an institution, network or partnership to facilitate adaptation.

1.1.5.2 Targeting of the EbA Projects

Though the projects were included in the UNFCCC database as examples to be drawn upon for adapting to climate change, the projects vary substantially as to whether or not they directly target climate change (Figure 4). In terms of the primary objective, 44% [19 of 43] of projects' main aim is to address climate conditions (current or future), and thus were coded as having a 'climate focus'. For example, Project #8 is designed as a direct response to rising sea level, increasing surface temperatures, and reduced rainfall arising from climate change. Twelve percent [5 of 43] of the projects primarily aim to mitigate the effects of natural hazards with limited consideration of the contributions of climate change to natural hazards, and were coded as 'natural hazard focus'. For example, Project #2 focuses on seasonal wildfire management yet does not specifically address how climate change will affect wildfires. Thirty percent [13 of 43] of projects primarily aim to improve ecosystems, or livelihoods and development, with limited consideration of climate change and were coded as having a "development/ecosystem focus." For example, Project #29 engages in reforestation activities to improve local communities' socio-economic levels and to address problems caused by deforestation. The remaining 14% [6 of 43] of projects aim to address both climate change and either natural hazards, ecosystems, or development and were coded as having a "climate plus other focus." Though the primary objective of a project may not be to address climate change, that project may still provide adaptation benefits. For example, Project #32, which is coded as having an ecosystem-focus, implements ecosystem protection measures in a watershed with the goal of restoring livelihoods and hydroelectric power generation damaged by environmental degradation. While addressing specific climatic impacts was not an explicit objective of Project #32, the project notes that adaptation might be an unintended benefit of the activities undertaken.

In terms of temporal focus, 53% [23 of 43] of projects explicitly address future climate change, while the other 47% [20 of 43] of projects focus on adaptation deficits associated mainly with current climate variability. For example, Project #7 mentions assessment of current and future climate risk to crop and livestock production as one of the outputs for the project. On the other hand, Project #9 aims to increase overall resilience of the area's urban forests and includes no mention of the impacts of climate change. Climate-focused projects tend to have a temporal focus on future climate change whereas the development, ecosystem or natural hazard focused projects primarily address current climate adaptation deficits.

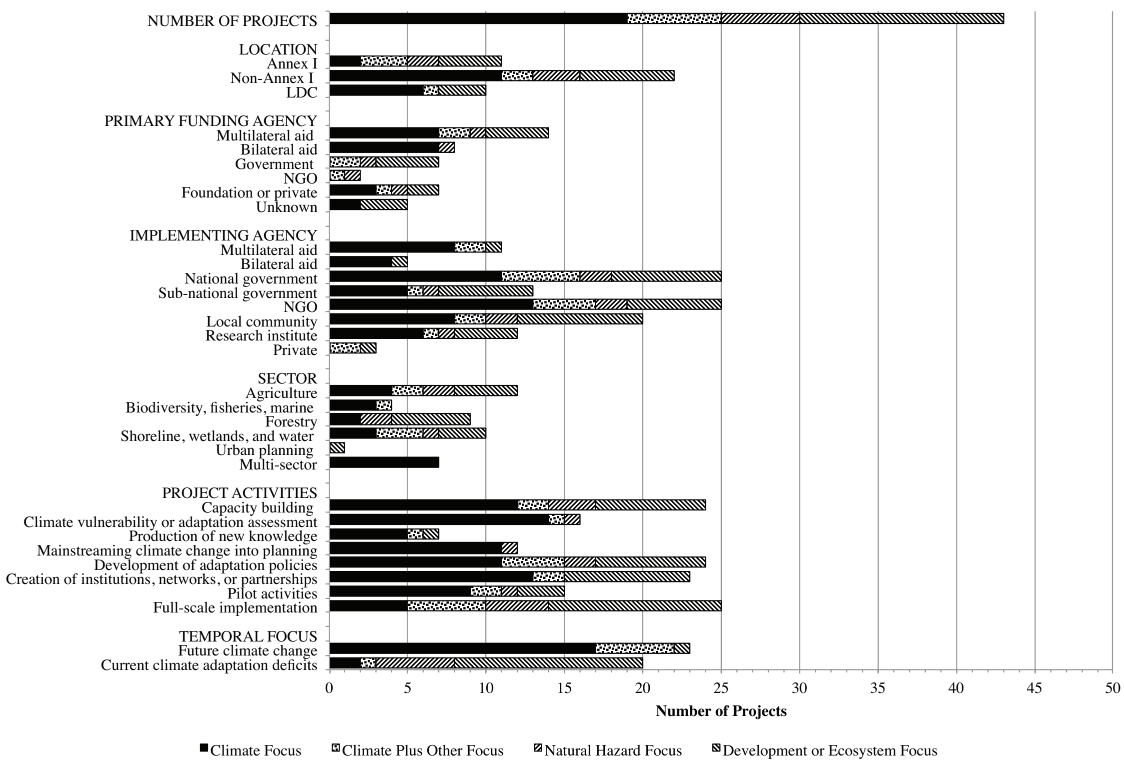

Figure 4: Location, Sector, Activities and Temporal Targeting of the EbA Projects. Bars represent the number of projects in each category. A number of projects are jointly implemented by more than one agency and each project may include more than one type of activity.

1.1.6 *Results: Information Used by the EbA Projects*

1.1.6.1 Specificity of Climate and Adaptation Information

Projects vary substantially in terms of the specificity of climate information used in the project's design (Figure 5). Information on expected future climatic conditions and sectoral impacts used by projects, ranged in their degree of detail from extremely limited data to comprehensive assessments. Forty-two percent [18 of 43] of projects did not make use of projections of expected future climate. Twenty-three percent [10 of 43] of projects rely on simple, macro-scale projections of future climate change such as expected average increase in annual precipitation for the country in which the project is located. Of these, seven projects involve large-scale direct implementation of adaptation actions. Thirty-five percent [15 of 43] of projects use more detailed regional-scale information, such as predictions of changes in seasonal precipitation and river runoff or in the frequency of extreme events. In terms of the impacts of climate change, 58% [25 of 43] of projects make use of information on how expected changes in climate will translate into specific sectoral effects, while the remaining 42% [18 of 43] of projects did not include detailed impact assessments.

Few projects address either the temporal uncertainties, the range of climatic conditions under which project activities will provide benefits, or the scale of intervention needed. Twenty-one percent [9 of 43] of projects mention uncertainty with respect to the timeframe under which climate change will be experienced. Fourteen percent [6 of 43] of projects address the time required for an adaptation intervention to be implemented and start producing adaptation benefits. Only 2% [1 of 43] of projects include consideration of range of climatic conditions under which intervention will be effective. Project #20 notes that the Maya breadnut tree, which will be used as an adaptive measure, can survive in temperatures of between 18-32°C and with precipitation levels of between 100-2500 mm/year. Five percent [2 of 43] of projects address the scale of intervention needed to provide benefits. For example, Project #11 uses information on the rate of saltmarsh loss from prior years to estimate the land area to that needs to be restored in order to achieve adaptation benefits.

Though the majority of projects did not address temporal uncertainties or adaptation effectiveness thresholds, 26% [11 of 43] of projects acknowledged uncertainties in broader terms. All of those projects had a temporal focus on future climate change and mentioned uncertainty either in their descriptions of expected future climate, their descriptions of expected local impacts or their descriptions of the long-term performance of the adaptation actions. For example Project #1 explains that "climatic future of the West African coastal zone is uncertain, and no single scenario can be provided at present. While temperatures and sea-levels are almost certain to rise, rainfall may increase or decrease, and circulation changes will influence ocean productivity in ways that are currently unclear" (United Nations Development Programme, 2006). While most of these projects do not explain how they address uncertainty, a select few projects state they account for uncertainty by adopting no-regret options; by focusing on shorter-term actions that would produce immediate results; or by preparing for worst-case scenarios.

1.1.6.2 INFORMATION USED IN DETERMINING PROJECT BENEFITS

Seventy-four percent [32 of 43] of projects contained sufficient detail in their documentation to assess information used for determining adaptation benefits. Of those, 53% [17 of 32] of projects explicitly describe how the activities implemented under the project will lead to long-term adaptation benefits. These assessments were either conducted prior to project implementation or were conducted after shortly after completion of the project. Nineteen percent [6 of 32] of projects estimate expected long-term benefits based on qualitative information and make reference to existing studies on the performance of the project interventions under climatic stresses similar to those that might be seen with climate change. Thirty-four percent [11 of 32] of projects discuss the expected long-term benefits using quantitative methods, usually cost benefit analysis that compares expected potential future impacts of climate change with the costs of undertaking the adaptation activities.

Seventy-two percent [31 of 43] of projects had sufficient detail in their documentation to assess information on the metrics used to track adaptation progress. Analysis of these projects suggests that monitoring and evaluation procedures undertaken by the EbA projects are limited. Thirty-nine percent [12 of 31] reported metrics that tracked both progress and effectiveness of the adaptation measures undertaken, 19% [6 of 31] measured only progress, and 19% [6 of 31] of projects measured only effectiveness of the adaptation actions. The remaining 23% [7 of 31] of projects did not report either progress or effectiveness metrics. Long-term monitoring and evaluation of project activities is not included as a component of most projects. Only 6% [2 of 31] of projects included concrete steps to track and monitor impacts for durations of 10 years or more after implementation. This limitation is not unrecognized by project implementers. For example, as explained by Project #11, "Over longer (+50 year) time periods, the increased defense efficiency [provided by this project] cannot be guaranteed, as continued landward retreat may be necessary to maintain an intertidal profile that supports saltmarsh vegetation" (ProAct network, 2008).

Despite uncertainty and a lack of monitoring, 79% [34 of 43] of projects do not discuss maladaptation. Of the projects that do address the topic of maladaptation, 12% [5 of 43] or projects acknowledged that project activities could have unforeseen negative impacts that could in turn increase vulnerability. For example Project # 33 states "Attempts to adapt to climate change may also be negative for biodiversity where approaches/adaptation responses drive agricultural expansion" (Petersen and Holness, 2010). The other 9% [4 of 43] of projects address the topic of maladaptation by describing how project activities aim to avoid current or change past maladaptive practices, yet do not acknowledge any potential maladaptive impacts of the project activities themselves.

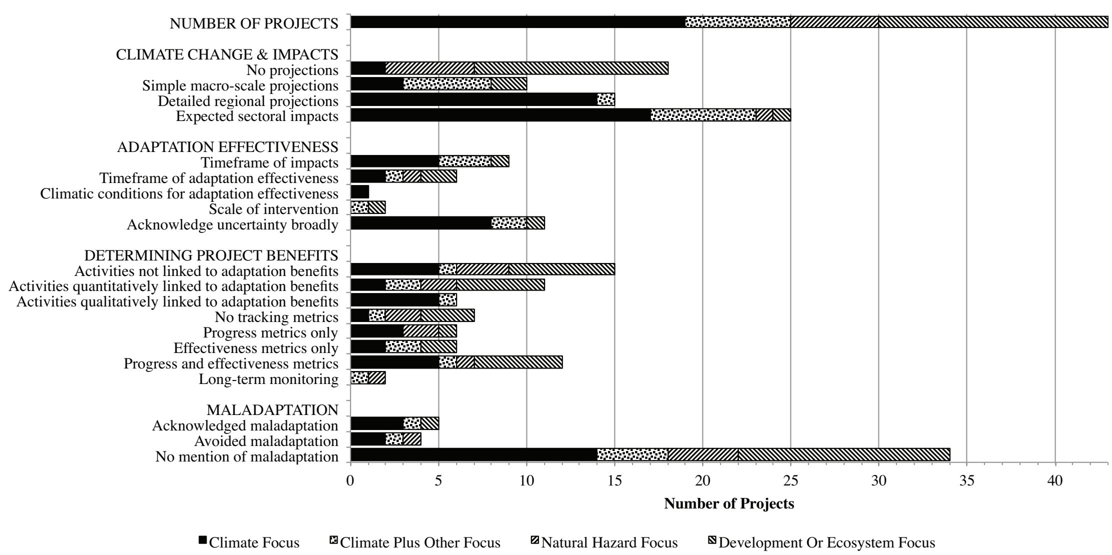

Figure 5: Information Used in the EbA Projects. Bars represent the number of projects in each category. Documentation from 32 of 43 projects included information on benefits and long-term monitoring, while documentation from 31 of 43 projects included information on monitoring progress and effectiveness. Therefore the results for these categories are based on a total of 32 and 31 projects respectively.

1.1.7 *Analysis by Country Group*

The conceptualization of EbA and information needs appears to vary across country groups (Table 2), though the small number of projects limits statistical analysis. EbA projects in LDC countries more directly address climate change. Seventy percent [7 of 10] of projects in LDC countries adopt a climate or climate plus focus in comparison to 59% [13 of 22] of projects in Non-Annex I and 45% [5 of 11] of projects in Annex I countries. Similarly, 70% [7 of 10] of projects in LDC countries have a temporal focus on future climate change, compared to 55% [12 of 22] of projects in Non-Annex I and

36% [4 of 11] of projects in Annex I countries. Moreover, 50% [5 of 10] of projects in LDC countries used detailed regional projections of climate change, compared to 41% [9 of 22] of projects in Non-Annex I and 9% [1 of 11] of projects in Annex I countries. However, there are fewer differences in the degree to which projects include information on adaptation effectiveness or maladaptation across country groups.

Location	**LDC**		**Non-Annex I**		**Annex I**	
Number of Projects	10	---	22	---	11	---
Primary Objective						
Climate focus	6	60%	11	50%	2	18%
Climate plus other focus	1	10%	2	9%	3	27%
Natural hazard focus	0	0%	3	14%	2	18%
Development or ecosystem focus	3	30%	6	27%	4	36%
Temporal Focus						
Future climate change	7	70%	12	55%	4	36%
Current climate adaptation deficits	3	10%	10	45%	7	64%
Information on Climate Change						
No projections	2	20%	10	45%	6	55%
Simple macro-scale projections	3	30%	3	14%	4	36%
Detailed regional projections	5	50%	9	41%	1	9%
Information on Climate Impacts						
Expected sectoral impacts	8	80%	13	59%	4	36%
Information on Adaptation Effectiveness						
Timeframe of impacts	1	10%	5	23%	3	27%
Timeframe of adaptation effectiveness	0	0%	3	14%	3	27%
Climatic conditions for adaptation effectiveness	0	0%	1	5%	0	0%
Scale of intervention needed	1	10%	0	0%	1	9%
Acknowledge uncertainty broadly	4	40%	5	23%	2	18%
Maladaptation						

Acknowledged maladaptation	1	10%	4	18%	0	0%
Avoided maladaptation	1	10%	3	14%	0	0%
No mention of maladaptation	8	80%	15	68%	11	100%

Table 2: Conceptualization of Adaptation and Information Used in EbA Projects By Country Group

1.1.8 *DISCUSSION*

The 43 EbA projects in the database vary considerably in their conceptualization of adaptation as well as in their use of information. The breadth of targeting of the projects indicates the UNFCCC is promoting an inclusive definition of EbA that includes both projects that directly aim to address current or future climatic conditions and those for which climate adaptation is not the primary intention. As the purpose of the database is to disseminate information on climate change adaptation this finding is noteworthy for two reasons. First, this broadly encompassing conceptualization implies the assumption that if a project builds or restores ecosystems services it also contributes to climate change adaptation. Second, it suggests that even when projects are identified as climate change adaptation, they may not include an explicit and critical analysis as to how they provide or contribute to responding to climate change.

In terms of differences in adaptation targeting across project locations, a greater percentage of the projects implemented in LDC and Non-Annex I countries have addressing climate impacts as their primary objective and future climate change as their temporal focus. In contrast, a greater percentage of the projects implemented in Annex I countries have addressing natural hazards, development or ecosystem resilience as their primary objective and current climate adaptation deficits as their temporal focus. The reason for this trend merits further investigation. As the EbA projects in Non- Annex I and LDCs are primarily financed by multi- and bi-lateral funding agencies, this finding may reflect the perspective that international funds used towards adaptation must have a clear climate change objective. It may also reflect a tendency for Annex I countries to focus on adaptation as an ancillary benefit, either because doing so aids in integrating adaptation into existing management processes (Klein R.J.T. et al., 2014) or because selecting strategies based on their non-climatic benefits is seen as most appropriate in the face of uncertainty of future climate change.

In terms of information used, only a small percentage, 35% [15 of 43] of projects, utilized detailed downscaled climate projections, suggesting that a lack of detailed information on expected future climate is not prohibitive to implementation of EbA. Though an explanation for the limited use of detailed climate projections by the EbA projects cannot be gleaned from the documents analyzed, prior research suggests that detailed climate projections are not specifically tailored to end-user needs, and therefore are often inappropriate for use in site or context-specific decision making (National Research Council, 2012). It is also possible that such detail is unnecessary for design and implementation of the EbA projects in the database. As illustrated in Figure 5, there is a strong connection between how adaptation is conceptualized in a project, and the project's information needs. Natural hazard, development and ecosystem focused projects are less likely to use detailed climate projections than projects that are climate-focused, in part because they tend to focus on current climate adaptation deficits rather than future climate change.

Uncertainty is broadly acknowledged in only a sub-set of the projects. The lack of attention to uncertainty across all project locations and sectors suggests that project funders are either willing to tolerate a high degree of uncertainty or are unaware of it. As uncertainty is acknowledged more frequently in projects that are climate-focused than in projects that are natural hazards, development or ecosystem focused, it may be that funders and implementers of projects for which climate adaptation is a co-benefit are less concerned with uncertainty then those seeking to directly address climatic conditions. Where uncertainty is addressed, there is greater attention to uncertainty in climate conditions then in adaptation effectiveness or the potential for maladaptation. This points to a need to more closely examine if the perceived need to initiate action leads funder and implementers to tolerate uncertainty in adaptation outcomes. Funders may require more specific, reliable, and accurate information on climate impacts and adaptation effectiveness, as adaptation efforts develop over time.

Lastly, with respect to improving the knowledge base of EbA, long-term monitoring and evaluation appears to be beyond the scope of the EbA projects. While monitoring and tracking adaptation is complex, a range of measures are available to assess the various stages of adaptation (Ford et al., 2013). The prevalent lack of monitoring included in the EbA projects, both in terms of the quality of metrics used, as well as the temporal scale of monitoring, highlights the possibility of a gap between expected and realized adaptation outcomes. This gap is especially problematic given a majority of the projects do not acknowledge the potential for maladaptation and therefore are not sufficiently considering the potential for unintended or adverse consequences arising from EbA.

1.1.9 *Conclusions*

By examining the projects identified by the UNFCCC as examples of EbA, our analysis has provided improved understandings of how the international climate change community conceptualizes EbA and what information is used in the design and implementation of EbA. However, a limitation of this research is that while the analysis encompasses a wide cross section of projects funded and implemented around the world, it is a curated selection of projects that reflects the UNFCCC's perspective.

The broad and inclusive conceptualization of EbA by the UNFCCC allows for a great variety of projects to be described as EbA; however, such an all-encompassing definition is not without implications. This wide variation in how EbA is conceptualized may make it difficult to identify or differentiate adaptation projects from ecosystems resilience or conservation or development projects. It also makes it difficult to compare, monitor and assess EbA. For EbA to become a more useful organizing principle, either its conceptualization needs to be narrowed, or a framework that distinguishes and categorizes activities falling within the broader umbrella of EbA needs to be developed. Such a framework would facilitate comparisons and evaluations of EbA and thus provide valuable information for decision-makers as they select, design and implement adaptation projects. It would also aid in assessing the extent to which investments made are reducing vulnerability, examining whether new agreements in the global arena are translating to actual adaptation, and identifying further actions that are needed to effectively adapt to climate change.

In terms of information needs for EbA, the specificity of information used in these projects varies depending on the targeting of adaptation. Only a very small percentage of projects used detailed climate projections suggesting that the design and implementation of current adaptation projects is not always informed by the latest climate science. This may suggest that current science is not yet usable in site or context-specific decision-making or that such details are unnecessary for design and implementation of the EbA projects in the database. Our analysis also shows that uncertainty is not well acknowledged in the projects.

Given the limited knowledge base on EbA (Doswald et al., 2014), greater evaluation of adaptation effectiveness is needed to ensure that implementation leads to the intended outcomes. Funders and implementers should incorporate post-implementation evaluation into the design of EbA projects in order to help identify the thresholds of effectiveness of EbA and to illuminate factors influencing the efficacy of EbA. Lessons learnt from projects can help ensure that later efforts avoid past mistakes and facilitate future implementation.

Ecosystems and the services they provide have a high potential to contribute to adaptation to climate change. As such, international organizations are actively promoting and investing in EbA. Increasing the knowledge base on exactly what EbA entails, its limitations, and the circumstances under which it will be most effective, will help move towards effective implementation of ecosystems based adaptation efforts.

CHAPTER 2

2. IDENTIFYING DECISION MAKERS' CLIMATE INFORMATION NEEDS

One of the main findings from Chapter 1 was that current adaptation projects do not incorporate detailed climate projections and impact assessments, and hence are not being informed by robust climate science. A logical next question to ask is why these adaptation practitioners did not use the latest scientific developments on climate change while designing their adaptation efforts. Chapter 2 focuses on my engagements with decision-makers in the agriculture and water resources management sectors, to understand the types of climate science that can be useful or not useful for adaptation planning. Here, I identify these decision-makers' specific climate information needs, and also discuss the types of engagement processes that enable effective elicitation of users' climate information needs. Chapter 2.1 analyses the types of long-term climate projections that farmers and farm advisors may find useful for on-farm adaptation decisions. This chapter uses semi-structured exploratory interviews as a means to investigate the utility of complex climate information to farmers. Chapter 2.2 presents a case of 'co-production' where water managers and climate scientists worked jointly and deliberately to identify decision-relevant metrics for adaptive water management.

Chapter 2.1 is currently being finalized as a manuscript with UC Cooperative Extension Specialist Dr. Tapan Pathak. This paper is included here with the permission of my co-author. For this project, I led the research design, development of the interview guide, conducted the interviews, analyzed the data, and wrote the paper in collaboration with Dr. Pathak. Human Subjects Approval has been obtained for this project from UC Berkeley's Institutional Review Board, Protocol # 2015-11-8110, titled "Bridging the gap between climate model outputs and farmers' information needs".

Chapter 2.2 has been submitted for peer review, and has been included here with the permission of my co-authors Dr. Andrew Jones and Dr. Isha Ray. For this paper, Dr. Jones and I co-led the design and facilitation of the co-production project and the various engagement activities. Other activities including data analysis and development of manuscript were conducted in collaboration with Dr. Jones and Dr. Ray. Human Subjects Approval has been obtained for this project from Lawrence Berkeley Lab's Institutional Review Board, Protocol ID: Pro00023082, titled "Stakeholder Engagement to Develop Use-Inspired Science", Protocol File Number: 353H002.

CHAPTER 2.1.

2.1 ASSESSING THE UTILITY OF LONG TERM CLIMATE INFORMATION FOR FARMERS USING EXPLORATORY INTERVIEWS

2.1.1 *INTRODUCTION*

As farmers across the world grapple with the impacts of climate change, there is an increased urgency to implement and accelerate agricultural adaptations (Hatfield et al., 2011; Howden et al., 2007; Pathak et al., 2018; Porter et al., 2014). A growing body of literature suggests that information on expected future climate change can potentially assist farmers in making adaptive on-farm decisions (Hansen, 2002; Jones et al., 2000; Mase and Prokopy, 2013; Prokopy et al., 2013). Climate projections can help farmers to make planting or management decisions that can avoid the negative impacts of climate change, and take advantage favorable conditions (Hansen, 2002; Jones et al., 2000). The growing scholarship on 'climate services'[5] and on developing actionable climate knowledge for farmers has, in the last decade, made several advances in understanding farmers' perceptions of climate forecasts, their specific decision-contexts, and providing them with tailored forecasts (Doll et al., 2017; Mase and Prokopy, 2013; Podesta et al., 2002; Prokopy et al., 2017; Vaughan and Dessai, 2014). However a majority of this literature currently focuses on a very small subset of climate information that is the seasonal forecasts, with only a handful of projects focusing on longer time-scales[6] (such as decadal or longer) (Hansen, 2002; Mase and Prokopy, 2013; Singh et al., 2018). The underlying assumption in this focus is that farmers typically plan on a year-to-year basis, and hence may not have much utility for longer time-scale information. A further assumption is that there is not enough 'certainty' in such longer-term projections to be useful to farmers (Nissan et al., 2019).

The sole focus on seasonal climate forecasts without simultaneously thinking about longer time-scales can be problematic because these short-term coping mechanisms can potentially preclude the crucial window of opportunity to undertake more transformational adaptation strategies. For example adapting to the next dry season may not necessarily be the same as adapting to a future where 13 out of the next 20 years are predicted to be dry (even if that prediction is only 50% likely). Several scholars have argued that effective adaptation strategies for the future necessarily require decision-makers to also think about longer time-scales (Adger et al., 2005; Dessai et al., 2009), and completely ignoring the longer term trends in climate can prove very costly as evidenced by the economic impact of the 2016 drought on California's agriculture which led to $603 million in additional costs and about 5000 farm-based jobs lost in the state (Medellín-Azuara et al., 2015, 2011). Recent research, such as those on robust decision-making frameworks, suggests that despite uncertainties, long-term projections can still provide information on broad trends that help in better planning or preparation (Dessai et

[5] Climate services is defined as the provision of timely, tailored information and knowledge to decision makers (generally in the form of tools, products, websites, or bulletins), which is an important part of improving capacity to manage climate-related risk (Vaughan and Dessai, 2014).

[6] For the purposes of this paper long-term or longer-term projections are referred to as projections of climate at a decadal or longer time-scales.

al., 2009, 2005; Lempert et al., 2013; Lempert and Groves, 2010), as long as they are used in an appropriate and pragmatic manner. Such information can be potentially be useful for certain types of long-term decisions or adaptations e.g. risk management, hedging, planting locations, making larger capital investment decisions, choosing resilient crop varieties, etc. (Crane et al., 2010; Howden et al., 2007; Nicholas and Durham, 2012). The main argument being that informed decisions about an uncertain future may be better than uninformed decisions.

Despite its potential utility, farmers' long-term climate information needs can be difficult to elicit, because they may not always immediately know the types of science that could be most useful to them, and whether science can provide such decision-relevant information with reasonable skill (Briley et al., 2015; Porter and Dessai, 2017). A related challenge is also that crop-specific actionable climate projections (i.e. projections that cater to crop-relevant climatic metrics, time scales, spatial scales and skill levels) are not readily available in the scientific literature (Crane et al., 2010; Roncoli et al., 2009), hence interpreting the potential utility of hypothetical projections can be difficult. Further, there is a large variety in types of farms and types of farming decisions, each requiring very specific types of climate information. E.g. perennial tree crop growers may have different planning time-scales and information needs than annual farmers. On the other hand, there are several different types of 'long-term climate information' each with a different utility for the farmers/farming decision (Crane et al., 2010; Hansen, 2002; Roncoli et al., 2009). E.g. the utility of projections from agro-climatic metrics such as growing degree days or chilling hours, are different than projections of physical climatic metrics such as average seasonal temperatures, or changes in physical climatic phenomenon like El-Nino. Hence identifying which types of projections are useful and for what purposes, can be very challenging, and necessarily requires iterative interactions between the science and farmers' decision-making contexts.

Further, most studies that suggest that uncertainty in projections are likely prohibitive, are based on climate modelers views of uncertainty and its implications to farmers (Nissan et al., 2019). There is very limited work specifically on farmers' tolerance for uncertainty in long-term projections, especially considering that farmers understand and work regularly with uncertain predictions in terms of weather forecasts, future market prices, etc. Considering the urgency for adaptation, and the long investment time frame of some of the decisions that they make today (e.g. buying land or irrigation equipment), the preferences of the ultimate user and their perception of uncertainty would be crucial. Yet, the literature is almost dismissive of farmers' agency in evaluating the usefulness of such information, and fails to shed light on whether and to what extent a farmer would prefer to know or not know about uncertain and imperfect long-term climate change projections.

Despite the complexity (and ambiguity) surrounding the topic, very few studies have engaged in detailed interrogations of the long-standing assumption that long-term information is not useful for farming decisions. The few studies that engage in trying to understand the potential utility or use of long-term information, often use surveys with narrowly framed questions to gather farmers' perception of such information. Further, these surveys often refer to long-term projections in broad ambiguous terms such as utility of "annual or longer term outlooks" (Lemos et al., 2014; Prokopy et al., 2017,

2013) or simply "climate forecasts" (Lemos et al., 2014) or even broader "weather/climate information" (Prokopy et al., 2017). While such questions are appropriate for understanding utility of forecasts on seasonal or annual time-scales, they may not be the most accurate representation of long-term shifts in climate such as increase or decrease in temperature or precipitation in decadal time-scales. This literature has started to acknowledge the limitations of such surveys, and has recognized the need for more qualitative ethnographic methods (such as interviews and focus groups) to better understand how farmers may incorporate climate predictions into their cultural, cognitive and decision-making landscapes (Crane et al., 2010; Doll et al., 2017; Roncoli, 2006). However, these ethnographic studies have not interrogated the utility of long-term projections, and have mainly been used to further the research on seasonal forecasts (Crane et al., 2010).

In this paper, we explore the utility of different types of 'long-term' climate projections, for on-farm adaptation decisions, using the case of almond tree crop growers in California. Through semi-structured exploratory interviews with farmers and farm advisors, the paper explores how farmers perceive the form, use and accuracy levels of long-term climate projections. Using interviews as a tool for 'joint construction of meaning' (Mishler, 1991) of different complex terms such as 'long-term climate projections' and 'long-term decisions', this research attempts to identify the types of information that can potentially be useful for on-farm adaptive decisions.

2.1.2 *METHODS*

This study focuses on almond crop farmers and farm advisors in the central valley of California. According to the California Almond Board, there are more than 283,000 hectares and approximately 6,000 growers of almond orchards in central California making it the world's largest producer of almonds. California is the only place in the United States where almonds are commercially grown and it produces about 80% of the world's almond supply (Almond Board of California, n.d.). Almonds are a long-lived crop with a lifetime of 25-30 years. The trees need to grow for at least 3-4 years before they can bear fruit, and do not provide a return on investment for several years after planting. Therefore, farmers are locked in for decades once they have planted the crop (Ames and Dufour, 2014). Unlike the annual crop growers who can change their decisions on when to plant or what variety to plant every year, adoption of climate resilient crop varieties by almond growers are far more difficult and slower (Lobell et al., 2006). Any changes in climate within the 25-30 year lifetime can hence have an adverse impact on crop yield (Luedeling et al., 2009a). Specifically, varying late winter and spring weather conditions have been known to result in lower yields for almond trees (Geisseler and Horwath, 2011). Hence providing almond farmers with information on long-term climate projections can potentially help them make decisions on which crop varieties or rootstocks are better suited for the future, what additional costs they may have to incur on increased irrigation water, and whether and how they need to change their farming practices in the long-run. (Lobell and Field, 2011; Luedeling et al., 2009a).

Semi-structured exploratory interviews were conducted with 11 farmers, and 5 farm advisors across the central valley of California between January and April 2016. This was during the last year of the 2011-2017 California drought, where a strong El-Nino was predicted but it brought lesser than expected precipitation (Siler et al., 2017). The sample of farmers was non-random and purposive, and they were contacted with the help of the UC cooperative extension. The sample included farmers of various age groups from late 20s to over 60s, farm sizes ranging from 60 to 3000 acres, and farmers with over 40 years of experience as well as early farmers. Several of the farmers grew other tree and row crops in addition to almonds, although almonds were the major crop. There were 7 almond crop advisors in the UC Cooperative extension in 2016, and 5 of them agreed to participate in the interviews. The farm advisors also spanned various age groups and were in-charge of different counties across the central valley. These farm advisors are experts in both research and bringing research to on-farm practice, they have advanced degrees in agriculture, pest management, soil sciences, etc., and had varying levels of understanding of climate change and climate change projections. Some were used to working with such data closely, while others understood the concept more theoretically without having delved into the climate data extensively. Farm advisors are considered as key intermediaries or information brokers for climate information as they are often considered farmers' trusted advisors (Lemos et al., 2014; Prokopy et al., 2013). Hence their opinion on potential utility of climate information to farmers was also gathered. Two interdisciplinary researchers, one of whom was a climate adaptation expert with the UC Cooperative Extension, conducted the interviews.

Each interview was about an hour or an hour and a half long, where the objective was to gather rich and nuanced understanding on farmers' preferences for long-term information. The interview guide included questions on key factors affecting farmers' decision-making, key issues faced by farmers in the last few years, farmers' use of used weather/climate data in the past, the impacts of climate change they may have experienced in the past, the climatic metrics that are of relevance to their crops, and finally the potential utility of different types of climate projections for decision-making (including perceptions of uncertainty, time-scales of relevance, preferred communication methods etc.). While theses broad themes remained the same in most interviews, since they were exploratory, the actual questions during the interview were more iterative, and guided by the interviewee's answers. This was based on Mishler's interviews as a 'joint construction of meaning' approach, where both questions and responses on 'potentially useful long-term projections' were developed and shaped by the discourse between interviewers and the interviewees. For example, in several interviews the farmers were asked about the utility of hypothetical long-term projections of certain climatic metrics. The actual climatic metrics presented during these discussions varied from farmer to farmer, as they were structured based on the metrics that the farmers themselves stated as being important for their crop. This approach was invaluable in the interview, as it allowed for contextualizing the projections to individual farmer's preferences (in a sense also jointly create new potentially useful projections), beyond just a few interviewer-driven projections. The interviews also involved a lot of clarifying, probing, iterative back-and-forth discussions, and mutual learning between the interviewer and the interviewee. For example, several interviewees asked the interviewers to help provide a better understanding climate models, what they are able to predict, what kind of uncertainties there are, etc. And the interviewee was also probed with several different types of potential climate projections, to gather their comparative utility to decision-making. Such detailed two-way discussions were critical as it allowed for the interviewers to reformulate questions and respondents to reframe answers, based on their reciprocal understanding as meanings emerged during the course of the interview (Mishler, 1991).

The interviews were audio-recorded, transcribed, analyzed and coded thematically. Since the interviews were exploratory, our findings are focused on the qualitative aspects of the interviews and we do not present numbers for every section. The next section on key results from the interviews is framed under 6 key themes: Farmers' initial perception of climate projections, farmers' experience of changing climate, climatic metrics of relevance, utility of crop-specific projections, decision-making time-scales, and uncertainties in projections.

2.1.3 *RESULTS*

2.1.3.1 INITIAL PERCEPTION OF CLIMATE PROJECTIONS AS AN EXTENSION OF WEATHER FORECASTS

Weather forecasts and climate projections differ not only in the time-scales they encompass, but also in the form and type of information they provide. For example: weather forecasts on daily or weekly time scales can provide predictions of daily high and low temperatures and chances of rain. Seasonal forecasts or 30-, 60-, 90-day outlooks usually provide probabilities of total precipitation and temperature departing from normal (Source: National Weather Service, Climate Prediction Center). However climate projections on decadal or 20-30 year time scales often provide information on trends of increase or decrease in different climatic parameters, potentials of shift from historical conditions, increase or decrease in frequency of extreme events or extreme hot days, etc. Although climate models can technically provide data for daily high and low temperature (if the models output daily time scale information), a 'climate change projection' often refers to information on shifts or trends rather than absolute daily predictions. However, this distinction between the form and format of climate versus weather forecasts was not immediately obvious to the farmers or the farm advisors, which was exemplified in the interviews.

Some of the initial questions in the interview sought to gather perceptions on utility for long-term temperature and rainfall projections at decadal or longer time scales (10-30 year time periods). These initial questions were phrased in a broader manner to allow for and understand different interpretations of the term, while some of the questions later on in the interview, were phrased more specifically. The interviewees were provided with a basic definition of weather versus climate, and examples of climate projections e.g. "trends of temperature in longer climatic time-scales", and were asked whether they have used or will likely find use for "trends of temperature or precipitation in longer time scales say decadal or longer time scale climate projections". At this stage, most of the farmers initially perceived long-term projections to be similar to 30- or 90-day outlooks or El Nino forecasts but for annual or longer time-scales. And based on this interpretation of 'long-term projections' suggested that they would not find such information useful, as they were unsure of the skill of such forecasts. In the subsequent discussions in became apparent that the National Weather Service has a Climate Prediction Center, which provides 30-day or longer outlook. These are commonly termed as "long-range forecasts" in the agricultural community, which then led to farmers conflating these with long-term climate projections. Therefore although the farmers' initial reaction to long-term climate information was not positive, they were actually referring to seasonal or annual scale forecasts, not the long-term projections that the interviewer had in mind. To illustrate: when asked whether they used or would like to use long-term projections, Farmer 3 said:

> *"No, I don't believe them most of the time. This year they kept predicting there's going to be an El-Nino, well I probably believe that but it does not tell you if its going to be a wet or a dry El-Nino, so we don't subscribe to those forecasts." (Farmer 3)*

Even farm advisors, who well aware of climate change concerns, were not very conversant with how the data on climate projections may look like. Two of the 5 farm advisors had a prior working knowledge with climate change projections and hence their interpretation of 'trends in temperature' matched those of the interviewer. Out of the rest, two advisors asked to clarify what the interviewer meant by long-term trends on temperature, and the fifth advisor conflated a long-term climate projection to a weather forecast at longer time-scales. Some of these pre-existing interpretations only came to light, after several probing discussions during the interview. For example, initially the Advisor 2 suggested that such climate change projections were not useful as it would be *"hard to base long-term capital investments on something that is still evolving as a science"*, and even equated basing decisions on long-term projections to basing investments on the predictions of the stock market. However, towards the tail end of the interview, Farm Advisor 2 stated that long-term projections can be useful if they are presented as *'potential for shifts'* in climate to occur. This is when their preconceived notion of a climate projection became apparent.

> *"It is not so much that the prediction is that in the next 3,4 or 10 years the temperature is going to be this, but that farmers practices must include the potential that there would be these shifts. I think that is a better argument, and farmers will respond to an argument like that, rather than saying hey, in 20 years the temperature is going to be 49 degrees on Feb 22 or something like that." (Farm Advisor 2)*

In summary, the interviews suggested that both farmers and farm advisors both interpret long-term climate projections as extensions of weather forecasts. This interpretation, while not always incorrect, is not the type of long-term projections that can provide the most skilled information to farmers about long-term changes, resulting in the interviewees questioning the accuracy of such information. Further, it reveals that farmers' and farm advisors' hesitation in using long-term projections is more a skepticism of seasonal or long-range forecasts than of the long-term projections in the form of trends or potentials of shift in conditions (this is further exemplified in subsequent sections).

2.1.3.2 MOST FARMERS EXPERIENCE CHANGES IN CLIMATE, AND IDENTIFIED FARM-LEVEL CLIMATIC IMPACTS

Despite the fact that most interviewees' initial reaction to long-term projections was not positive, when asked whether they have experienced any long-term gradual changes in climate such as warmer winters or lesser fog, all the farmers (without exception) and most of the farm advisors agreed that they have been seeing these changes. In fact most of the farmers explained in great detail, how they have seen a reduction in fog and a reduction in chill hours compared to the past. Other key climatic changes that were mentioned included: very hot summers, lesser rains, increase in days over 90 or 100 degree F, etc. This finding is similar to other studies which have also found that despite farmers' perceptions of climate change, a majority of them report experiencing climate impacts on their farms (Arbuckle et al., 2013; Doll et al., 2017; Prokopy, 2014). Farmers made statement such as:

> "*Winters are definitely drier and they are warmer"* (Farmer 5),
>
> *"It has definitely been weird the past few years"* (Farmer 4),
>
> *"Although I have not really looked at trends (data), I kind of mentally do, and it seems like winters are definitely trending warmer"* (Farmer 3).

Most farmers followed up their observations of changing climate with mention of specific farm-level climatic impacts. Several suggested that their peaches and pistachios have suffered due to reduction in chill hours and that it was likely to deter them from planting those again. Others mentioned crop-specific impacts such as almond flowers blooming earlier and quicker, earlier harvests, and change in disease regimes as evidenced by a change in pesticide spray timings. Further, they also suggested that these impacts were likely becoming regular phenomena. Some statements made by farmers were:

> *"Last year, bloom was pretty early and the year before it was like a flash"* (Farmer 4)
>
> *"In the last four years bloom has moved up, Harvest used to be towards the end of August now the norm in August 15th, its been that for the last 4-5 years. We have always had an early year in the past, but now it's like the early years becoming the normal."* (Farmer 5)

While the farm advisors also agreed that farmers may be experiencing such impacts, they also suggested that information about these impacts was not yet being incorporated in their planning.

2.1.3.3 CLIMATIC METRICS OF RELEVANCE TO FARMERS

In order to gain perspective into the climatic parameters that were of relevance in the life cycle of an almond tree, the interviewees were asked to identify 4 or 5 key climatic metrics that were crucial for optimal growth of their almond trees. Aside from the daily temperature, humidity, evapotranspiration and rainfall which were identified as "generally useful" on a day-to-day basis, farmers and farm advisors identified metrics such as chill hours, low-temperatures during winters, frost during bloom, rains during harvest, humidity at harvest, high temperatures in summer, extreme heat days above 90 or 100 degree F, optimal bee-flight conditions during pollination, wind, etc. as critical metrics for the almond crop. Figure 6 shows some of these crop-specific metrics:

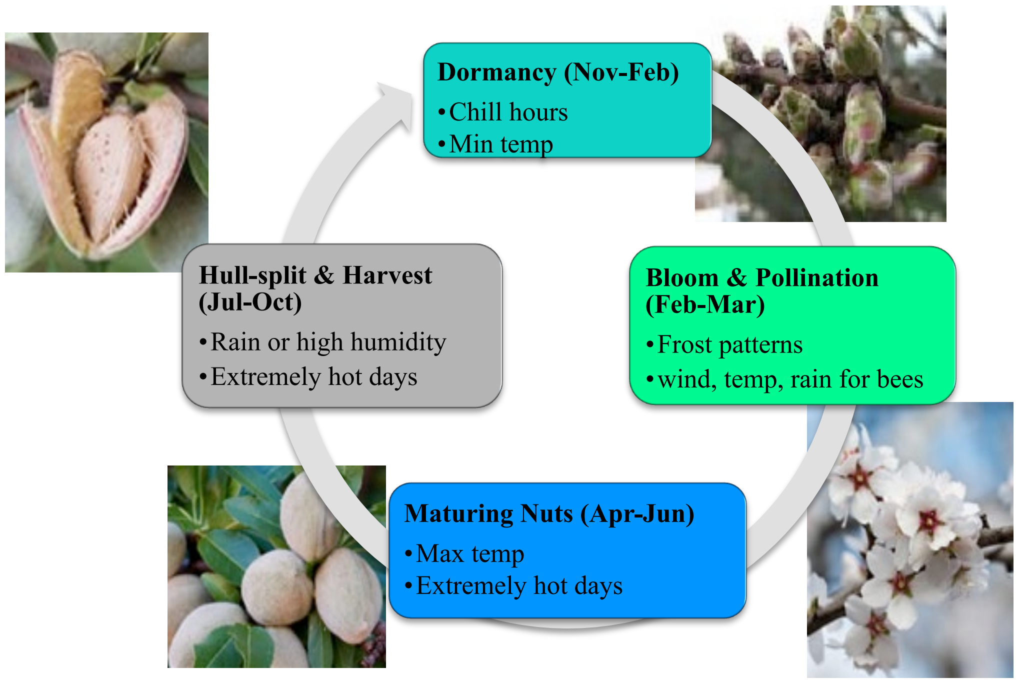

Figure 6: Climatic metric of relevance for the almond crop as identified by farmers and farm advisors.

2.1.3.4 Crop-specific projections are very useful to farmers

Despite the initial negative reaction towards the broader suite of 'long-term projections' phrased in a more generic manner, the main aim of the interviews was to understand whether some specific types of projections may be useful to farmers even if generic ones are not. Therefore in this part of the interview, the interviewer engaged the farmers in discussions of different types of 'hypothetical' projections specific to the climatic metrics that the farmers identified as relevant to their operations. This phase involved several variations of questions such as *"what if I could tell you something about xyz climatic metric, and whether it would increase or decrease in the next 10-20 years"*, through iterative interactions with the farmers, in order the identify the most useful types of projections. In several of the interviews, the discussions started with the metric of chill hours as a starting point. This was because one of the interviewers had worked on chill hour projections and hence was most familiar with this data.

As a stark contrast to the initial negative reaction to 'long-term temperature projections', when the interviewer asked if chill hour projections would be useful, all the farmers suggested that such information would 'absolutely' or 'definitely' be useful to them. The interviewer asked the farmers some variation of the following question.

> *"If I were to say that in the last 20 years chill hours have been reducing at a rate of approximately 10 chill hours per year, and that hypothetically based on climate model projections we can say that it is likely that a 5 to 10 chill hour reduction may continue into the next 20-30 years, is that information useful or informative to you"*

The response to this statement was overwhelmingly positive, and all of the farmers stated that such information would be useful. In fact, more than half of the farmers also suggested that it may make them change the varieties or crops they plant, the way the manage their operations or even prompt them to not plant certain crops. Some of the farmer's responses are presented below:

> *"Absolutely. Because you know, I'm starting to recognize today just the difference in fog. When you really see so much difference in a short amount of time in your immediate area, absolutely. We would have to look at that and say, well, we're going to have to adapt varieties because this is a 20 or 25 year planting and we're going to have to find crops that or varieties that will adapt to that." (Farmer 1)*

> *"Yes, it would be yes. That would be the information that may stop your next planting of trees, but it has to come from the correct source." (Farmer 3)*

> *"I think it would be useful. Throughout our farm's history, we've grown more than 15 crops probably, because you adapt to whatever is best suited. So yeah, knowing what's going to happen or at least having a good idea, if you know something won't be viable, then obviously you're going to try to phase that out, and phase in something that's better suited." (Farmer 8)*

While the impact of the reduction in chill hours metric was more obvious to farmers, when some of the other climatic metrics were discussed, farmers suggested that the impact of their increase or decrease on their crops was not obvious. So farmers suggested that those projections be presented with information on their potential impact on crops, and possibly with potential adaptation measures on how such information can be used in decisions. In a discussion with a farmer about the metric of July maximum temperatures, the farmer suggested that:

> *"Just knowing that temperatures are going to increase by some degrees, I don't know what that's going to do to my trees. I mean if the trees have plenty of water will they be stressed, or will they still be fine? So knowing temperature is just half the equation. But in case you say well you will start seeing more diseases, and also what I can do to alleviate it then its useful – maybe I can reflect the sunlight or move to Oregon {laughs}." (Farmer 11)*

One of the most surprising findings of the interviews were that although all the farmers immediately took positively to the utility of long-term crop specific projection such as chill hour or summer heat changes, some of the farm advisors were a little more pessimistic about how farmers would receive this information.

> *"The utility probably depends on what they can do about it, some things are out of their control, they can't make it colder." (Farm Advisor 4)*

> *"You know I think it is certainly useful and interesting, but at least to my understanding growers would prefer fixes. I don't think there are very many people out there who will base a bulk of their financial decisions on that long-term situation."(Farm Advisor 2)*

This finding was interesting, and corroborates some recent studies that suggest that farm advisors in UC Cooperative Extension are often worried about how their clientele will react to climate change information (Grantham et al., 2017). However, the interviews show that farmers may be more open to hearing about crop-specific climate projections than the literature expects.

2.1.3.5 FARMERS' DECISION-MAKING TIME-SCALES, AND THE CONFUSION BETWEEN DAY-TO-DAY VERSUS LONG-TERM DECISIONS

Current versus future decision time-scales: A lot of the literature on climate information for farmers strongly suggests that farmers only plan on an annual basis or at the most for 3-5 years. Our interviews, to a large extent, also found that many decisions on the farm do have a shorter decision-making time scales. However it additionally also found that, when farmers hear about crop-specific long term impacts they are open to thinking about planning decisions for much longer time scales. This suggests that even if farmers have not planned for such longer durations in the past, climate change could prompt a change in these decision-making time scales. Most of the farmers, after they were presented with the longer-term crop-specific projections, showed that they were open to thinking about how they should manage or design their farm in the next 20-30 years. Some of the quotes in the previous sub-section highlight this, and the following excerpt from a back-and-forth conversation with Farmer 2, exemplifies this intent to change.

> *Farmer 2: " It is just so hard to look out into the future, I am more looking into the next 1-3 years rather than 10-20 years"*
>
> *Interviewer: "But what about these gradual changes we talked about like winters getting warmer and seeing less fog"*
>
> *Farmer 2: "Now that can be concerning because obviously we have crops in California for a reason and obviously if it starts getting too warm, too dry, too wet, you just can't grow the same crops obviously. So that is a concern. But how, how long until that happens, I don't know."*
>
> *Interviewer 2:"What if I were to tell you hypothetically that spring temperatures may go up by a couple of degrees in the next 10-20 years, would that be useful in your planning"*
>
> *Farmer 2: "I am really interested in that. But like I said, one to three year window is kind of what I look at right now. I really shouldn't be. Obviously you're planting perennial crops, like almonds tend to be in the ground for 20-30 year, so I should look further out, but right now my head is in the sand. I hate to admit it."*

What decisions can projections be useful for?: There was also confusion about the specific types of decisions that could be informed by long-term projections, which subsequently resulted in confusion about appropriate decision-making time scales for farmers. Farmers currently use weather forecasts for more day-to-day operational decisions, such as when to irrigate, and when to turn on frost protection devices. Hence their initial expectation is that longer-term climate will also help with similar operational decisions but for 20 years from now. However long-term climate projections are primarily useful for long-term planning and broader farm development types of decisions such as what varieties to plant, where to plant, how to change farming systems, etc. and this distinction is not readily obvious to farmers. In other words, just like the form of climate projections was perceived as an extension of weather forecasts, the use of climate projections was also sometimes perceived as an extension of weather forecasts. It also showed that ‘long-term decisions’ similar to the term ‘long-term climate projections’ was equally ambiguous and vague, as there was a confusion as to whether it meant an operational decision 20 years from now, or a completely different planning decision taking into account changes in the next 20 years.

To illustrate, a weather forecast for frost would tell a farmer about the likelihood of reaching dew point temperatures in the next day or two based on which farmer decides whether, when and how long they should operate their frost protection measures. On the other hand, a climate projection on frost would provide information on the likelihood of increase in frost occurrences in a month, and the farmer’s immediate reaction is to question how this information helps then decide when, and how long they should operate frost protection measures 15 or 20 years from now. However this projection of climate is not as useful for the ‘day-to-day’ or short-term decision of when to operate frost protection (20 years from now), but can certainly help farmers make long-term planning decisions such as whether they should change to a later-blooming crop variety or invest in a wind machine for frost protection or how often the farmer should expect to be using frost protection measures (Figure 7). The iterative discussions between the interviewer and farmers were able to clarify this difference in use for long-term projections, and with that clarification farmers were more receptive to thinking about longer-term decision-making. The following interaction with Farmer 6 highlights this confusion between day-to-day versus long-term decisions, and its relationship with decision-making time scales.

> *Interviewer: “If there was some long-term information about likelihood of increased unsettled patterns or rains in March or perhaps increase in summer or July temperatures in the next 20-30 years, would that be useful to you?”*
>
> *Farmer 6: “Oh definitely, lets say if we knew that in some year it was going to have a lot of unsettled weather in February and March in time for me to order bees, instead of two hives per acre I would order three hives per acre, but I cannot do that with like a weeks notice. I need to know before hand.”*
>
> *Interviewer: “Oh, but that might be a bit difficult, because actually the 20 year projections usually provide information on long-term trends and they may not be able to get the year-to-year very right. So they may say for example that by 2026 you might see an increased likelihood in March rains or something but not really say what will happen in 2020 or 2021.”*
>
> *Farmer 6: “Oh I see.”*
>
> *Interviewer: “So they may not be able to tell you say whether this season you will need more bee hives {referring to the shorter term or day-to-day decisions}, but they can maybe help plan the range of number of beehives you may require in the next 10-20 years.”*

Farmer 6: "Well I think it still applies, I might say well maybe I should be thinking about having more bees. In fact, maybe I should buy another spray ring because there is going to be shorter windows when I have to spray quickly {because weather may be unsettled}, that is certainly something I need to plan long-term. Also, maybe the next orchard I plant is a variety that is blooming later. So there could be implications."

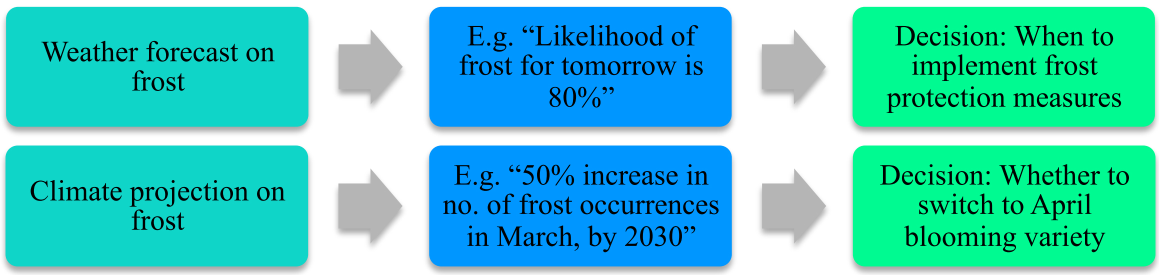

Figure 7: Figure illustrating the different between the form and use of a weather forecast versus a climate projection for frost.

Overcoming the 'you cannot change the weather' challenge: Another interesting way in which this confusion between day-to-day and long-term decisions manifested was the *"but you cannot make it colder"* roadblock that was often faced in the interviews with some farmers as well as farm advisors. This is a very commonly reported issue the literature (Doll et al., 2017), however the interviews showcase that this issue could be overcome through discussions about potential long-term adaptations based on the information. A handful of farmers and farm advisors, some times during the interview would often suggest that information on reduction of chill hours or increases summer temperatures was interesting and good to know, but that there was nothing one could do with it because *"it was out of their control*". While information about chill hours would have limited use for short-term or day-today decisions (as there are limited management options to cope with lower chill), such information could help farmers think about different crop varieties, or low-chill crop varieties. This was not always immediately obvious to farmers and needed some nudges from the interviewer for them to start thinking about such adaptive decisions. But once this intention was clear, farmers themselves came up with novel long-term uses for the information that the interviewers had not thought about.

2.1.3.6 Uncertainties and Inaccuracies in long-term information

Some of the most interesting and mutually beneficial conversations of the interviews were during the discussion of potential uncertainties and unknowns regarding long-term climate information. One of the biggest pushbacks against the use of long-term information for farming is the notion that such information is not accurate enough to inform various farming decisions. One of the goals of the interviews was hence to ask the farmers about their opinion on uncertainties in information, through a series of simple questions. While this extremely simplified questioning about uncertainty thresholds of farmers is by no means an exhaustive study in the matter, the responses from the farmers were still very useful to shed light on their broad perceptions.

Tolerance for uncertainties: In the interviews, the interviewer transparently communicated to the farmers that the projections of climate were not 100% accurate due to the uncertainties and inaccuracies in climate models, and unknowns regarding carbon emissions and other parameters. The interviewer then asked the farmers whether they were likely to use the long-term projections if there was only a 70% likelihood or confidence in such numbers (and there were always a certain error percentage associated with them). Surprisingly, almost all the farmers suggested that they understand that all future projections come with uncertainty and 70% and sometimes even 60% likelihood numbers would still be useful.

> *"If you put out confidence levels, I think everybody can evaluate for themselves. You don't have a crystal ball, but you can certainly extrapolate from the trends you are seeing. Sure." (Farmer 3)*

> *"The thing is that you never make a decision off of one piece of information. There's a whole lot of information that goes into a decision like that. So would that {60% likelihood information} be in the mix? Yes. Would it be at the top of the priority? I would say no." (Farmer 2)*

The in-depth discussions revealed that farmers perceived accuracy to be a key issue for short-term or day-to-day decisions, but for longer term planning decisions they were more tolerant towards uncertainties. Advisor 3 suggested that a 20% error in weather forecasts of frosts could mean a loss in complete crop loss, but if one is talking about changes in likelihood of frost occurrences over time then there is a bit more room to work with uncertainties. Longer-term planning decisions are often dependent on several variables, many of which are uncertain (like market prices), so as business people, farmers understand and work with such uncertainties all the time. The interviews also showed that farmers would still like to know 'uncertain' impacts or projections as long as the uncertainty ranges were transparently communicated. In fact one of the advisors even cautioned against providing projections that seemed too accurate, to avoid a *"boy who cried wolf situation"*, because farmers were aware that such absolute certainty may not be possible in the long-term.

Year-to-year values versus information about trends: Some literature suggests that climate projections in the 10-30 year time scales are not useful for farmers as these projections do not sync with the observations in terms of timing of modeled decadal and inter-annual variations (Nissan et al., 2019). While this means that climate models may not be able to accurately predict results on a year-to-year basis, but literature suggests that climate models may still be able to provide information on trends and potentials for shifts from historical conditions. The question then is, whether these broader trends are useful to farmers? We explore this in the interviews by asking the farmers whether projections would still be useful if they were unable to provide year-to-year absolute values and could only provide information about trends. Many farmers suggested that information on trends would be preferred for the long-term planning purposes.

> *"I think trend is more important than any specific point in time." (Farmer 11)*
>
> *"I think trend will be good and useful because for long-term planning you have to kind of guess and anticipate, and try to anticipate as best you can." (Farmer 8)*

Often times, this discussion would prompt the farmers to ask the interviewers to explain what the models did and why such uncertainties existed. These discussions showed farmers' interest in learning more about the models, and not only helped clarified model capabilities (in very broad terms), but in several cases also allowed farmers to empathize with why it was not possible to provide very accurate projections in long-terms.

What is more accurate, 10 year or 20 year projections?: Another interesting finding from the interviews were that often times, farmers and even some farm advisors suggested that they preferred shorter time scale information because they assumed that 5 or 10 year information was likely to be more credible than longer time scales. Hence, their perception of accuracy of climate projections was also an extension of the accuracy of weather forecasts where accuracy decreases with time. However climate models work differently, and often do not predict the nearer term variabilities such as 5-10 year times scales as well as they can capture broader trends in 20-30 years. When this was communicated to the farmers, they suggested that they would prefer to use the more accurate 20 year projections even if they would have ideally also liked to have 10-15 year time-scale information. Hence there seemed to be a trade-off between the temporal scale of information and its certainty. The following conversations with Farmers 4 and 5 shed light on this.

> *Farmer 4: "Well personally I may look at all, but if there is something we can look at more accurately in the 5 year or 10 year model then that's good, but I will be interested in the 20 year model too even if that's where things may get a bit leery because so many things change the further you go in time."*
>
> *Interviewer: "Well, that may not necessarily be true because the way these climate models work, we may actually be a bit more confident and see more of a signal on the 20 year time scale for trends anyway."*
>
> *Farmer 4: "Oh that's good to know that explanation has to be given, people are not going to know that right off the bat. And in that case that is more useful."*
>
> *Farmer 5: "Well, Yea I can understand {that longer-term trends may be more accurate than 10 or 5 years}, if some reason if you say had a wet El-Nino that plugged in a 22 inch rainfall it can screw up the 5 year average. But in the 10-20 year period it is not going to matter that much. So yea I would go with 10 or 20 then. Five years is going to be within that anyway."*

2.1.4 *DISCUSSION*

A large portion of the literature that assess farmer's perception of climate information, dismisses the potential use of long-term climate projections suggesting that farmers do not plan for such time-scales, and they are not likely to use such long-term information. Yet, most of these studies base their results using surveys as the main instrument of study (Crane et al., 2010; Mase and Prokopy, 2013; Prokopy et al., 2013), and very few interrogate why farmers' have these perceptions, and whether climate change impacts may alter some of their current decision-making patterns. Through in-depth exploratory interviews with almond farmers and farm advisors in California, we find that the terms "long term temperature projections", "climate projections", "long term decisions", etc., are complex and often ambiguous with multiple conflicting interpretations and meanings. This work finds that farmers often perceive long-term climate projections as extensions of weather forecasts even though the two differ significantly in their form, type of use, and uncertainties. This mismatch in researchers' versus farmers' interpretation of the term "long-term climate projections" is not well addressed in the literature. And these interviews have shown that understanding and acknowledging this mismatch is essential for trying to understand the actual utility of long-term projections for farm-level decisions. The results strongly suggest that if questions are asked without engaging in detailed discussions of what long-term projections really mean, it may lead to potential misinterpretation of farmers' perceptions, by equating farmers' perspectives on what they understand to be climate information (which is often seasonal forecasts) rather than their perspectives on the information on long-term crop-relevant shifts and trends that climate projections can often offer. Hence using surveys or structured interviews as a means to study this topic can be limiting or even problematic.

Further, in the handful of studies that use interviews as a means to ascertain farmers' perception on long-term information, this mismatch in interpretations of climate projections has not been thoroughly interrogated or expanded on. For example, the Doll et al 2017 study suggests that, farmers do not think of climatic time scales because they need accurate weather predictions at different time scales, since farmers suggested that *"it doesn't matter what the weather is going to be 20–30 years from now. It only matters what it's going to be next year, and nobody can predict that."* While accurate long-term weather forecasts may indeed be a critical requirement for farmers, this statement from the farmer shows that they perceive long-term climate projections to be similar to a weather forecast in 20-30 years, and that they are to be used similar to how they currently use weather forecasts. While this may well be one way of perceiving long-term climate projections, it is certainly not the only type of potentially useful projection, and most certainly not the only utility. Since these studies do not report on engaging in further conversations of crop-specific trends and how they might be used in planning or farm development decisions, it is difficult to ascertain whether or not farmers may in fact find utility in other types of long-term information.

The exploratory interviews conducted in this research, enabled the interviewer and interviewee to co-construct meanings for several terms related to long-term climate projections, which enabled the emergence of a shared understanding of what useful projections may look like, how they may be used, and what their uncertainties might be. This process clarified that long-term climate projections were not seasonal forecasts or weather forecasts in the next 20-30 years, but rather provided information on trends or potentials of shifts from historical conditions. It also clarified that such information was most useful for making long-term planning decisions on the farm rather than day-to-day or short-term operational decisions for several years from now. And finally, it helped elucidate that projections of climatic trends for 20-30 year time scales were likely to be less uncertain than shorter time periods (unlike the accuracy levels in weather forecasts that tend to decrease with time). This change in perception of the form, use and uncertainty of long-term climate projections was the critical turning point of the interviews. The trajectory of the interviews, and consequently farmers' perception of the utility of long-term climate information, completely changed once the farmers recognized these three key things: (1) that the long-term climate projections were not trying to predict high and low temperatures on Feb 22 in 2030, but were providing information on long-term trends that may be expected; (2) that this information could not be used for deciding how much to irrigate in Feb 2030, but rather to understand the possibility of a x% increase in irrigation requirements in the next 20 years which may help decide whether or not to invest in a different irrigation system; and (3) 20-30 year trends are often more accurate than 5-10 year information. Further when provided with narratives of potential shifts in crop-specific metrics such as chill hours or summer extreme heat days, the potential utility of the information enhanced even further. This also led to farmers themselves coming up with newer uses of long-term projections. In this manner, the iterative discussions in the interview not only led to a change in perception of utility, but also in gathering farmers perspectives on what useful long-term projections may look like, and how it can help make adaptive decisions. For example in one of the interviews, the farmer who was initially focused mainly on seasonal forecasts, towards the end of the interview suggested that several longer-term climate projections can in fact be useful to them for various adaptive decisions (many of which the interviewers had not thought of).

> *"Well one thing that when we talked about summer heat and your long-term forecast, let's say you're saying it's going to be this much hotter for longer time, then maybe I need to manage my irrigation such that I need to deliver water more rapidly so maybe I invest in two one gallon emitters instead of two half gallon irrigation emitter. So your forecasts can be making me make those changes if I could see that 10 or more years ago." (Farmer 5)*

In addition to expanding the scope of what long-term projections can potentially provide to farmers, the interviews also showed that farmer's are open to changing their decision-making time scales and practices in response to climate impacts and long-term climate information. Hence considering farmers' decision-making time scales and practices as fixed and immutable, may be limiting, as it does not acknowledge farmers' agency and willingness to change their practices in response to climate impacts. Doll et al 2017 conclude that while farmers acknowledged that they are always adapting (to climatic and non-climatic factors), they did not view themselves as having a great deal of agency when it came to climate change adaptation, as farmers suggested, *"You can't do anything about it"*. However these interviews show that if farmers are nudged and probed to thinking about potential long-term adaptations, one can get over the *"you cannot control the weather"* roadblock and in fact farmers even come up with novel adaptive solutions to long-term climatic changes.

Finally, the interviews also found that several of these challenges and ambiguities in interpretation were not unique to farmers, but were also prevalent with the farm advisors. This strongly indicates that the nature of the topic is such that it requires more open-ended conversations and clarification to understand the actual potential of long-term climate information to inform adaptive decision-making. The findings also showed that farm advisors were more pessimistic about farmers' perception of utility of long-term information, than the farmers themselves were. This is perhaps due to the fact that often times, long-term climate projections are only discussed with farmers alongside discussions of anthropogenic climate change. In this research, the interviewers took cues from earlier work (Arbuckle et al., 2013; Doll et al., 2017) that suggests that one can have fruitful conversations about adaptation and the use of climate projections, without debating the human causes of climate change. Training farm advisors on not just the potential uses of climate change projections, but also on how to engage in such mutually beneficial 'joint construction of meaning' conversations on climate change, may be crucial to improve the understanding of the types of long-term information that can aid farmers in agricultural adaptations. While, this research points to an overall potential for long-term information to be useful for farmers, it is to be noted that the actual utility will greatly depend on the extent to which scientists and boundary agencies can effectively develop, translate and communicate user-relevant long-term climate projections. While some types of potentially useful climate projections such as trends in temperatures may be easier to develop and communicate, other specific projections such as monthly rainfall trends, or frequency of extreme events, may be more difficult to develop. Despite these scientific limitations, this research shows that some farmers may still want to know about 'uncertain' projections (communicated transparently with their errors and confidence levels) due to its potentially high impact on their planning and operations. Farmer 11 and Farm 8 summarize this need for information that allows them to plan ahead:

> *"One of my biggest fears is that we will say ok we now have limited water supplies during the summer. So we're going to take that water for the cities and for the fish. If that's what society wants to do, that's fine. But I've invested in developing an orchard that I have been counting on getting the income back over 25 years. If you say you are turning the water off tomorrow, I'm screwed. But turning the water off slowly over the next 25 years, I can make capital decisions accordingly. We are not getting this information from anywhere." (Farmer 11)*

> *"At least here in this area, we would like to know things as far in advance as possible. Almonds are looking at a lifespan of 20 to 30 years, and at the end of its life cycle, if it's going to be, if it's not going to be suitable to plant something else that I need to come up with a plan to plant something else. But its not always that easy just to switch your operations, you know, maybe you might have to invest a lot of capital to, to grow something else, you need equipment you need and then you don't have expertise in it either, which is almost invaluable and takes time to build." (Farmer 8)*

2.1.5 *CONCLUSIONS*

The semi-structured exploratory interviews revealed farmers' perceptions on long-term information, uncertainty in projections, and potential use of such information for on-farm adaptations. The exploratory format enabled clarifying discussions and mutual learning between the interviewers and the interviewees, and led to 'joint construction of meaning' (Mishler, 1991) of various complicated concepts and terminologies, through iterative adjustments and improvisational responses between the interviewer and interviewee. This eventually enabled the joint identification of the types of climate projections that can potentially assist perennial tree crop growers' in making different types of long-term management and planting decisions. These results highlight the importance of, and even necessity for, using qualitative exploratory discussions to appropriately understand farmers' perception of long-term climate information. It further suggests that the mismatch between farmers and researchers' interpretation of long-term projections, its accuracy, and its potential use, could perhaps be the reason for farmers not recognizing the utility of long-term climate projections. More such exploratory, rich and probing conversations with farmers can help in better understanding their use for long-term climate projections.

CHAPTER 2.2.

2.2 Identifying decision-relevant climatic metrics for water management through co-production

2.2.1 *Introduction*

Adaptation practitioners and policy-makers seeking to act proactively in the face of climate change need decision-relevant climate information. However, there is frequently a mismatch between decision-makers' needs and the scientific information produced by climate scientists (Lemos et al., 2012). Climate modelling efforts typically provide information on metrics of climatological or meteorological relevance, such as averages or extremes in temperature and precipitation. Resource managers, however, prefer climatic metrics that provide actionable information (e.g. start date of the rainy season for irrigation planning) (Briley et al., 2015; Moss et al., 2019; Mote et al., 2011; Roncoli et al., 2009). Few studies have systematically identified decision-relevant climatic metrics for sectoral adaptations, or the processes by which these metrics can be identified (Hackenbruch et al., 2017; Vano et al., 2019). Moreover, such metrics can be difficult to elicit, because decision-makers do not always know the types of metrics that could be most useful, and scientists do not always know whether they can provide decision-relevant science with reasonable skill (Briley et al., 2015; Porter and Dessai, 2017). 'Co-production', or iterative and continual engagement between scientists and decision-makers, can be a way to bridge the gap between decision-makers' needs and scientific priorities, and to identify climatic metrics that contribute to decision contexts (Kirchhoff, 2013; Lemos, 2015; Nature (Editorial), 2018; Vogel et al., 2016; Weaver et al., 2014).

Despite their promise, recent literature suggests that co-production processes are not always successful at listening, understanding, and responding to, decision-makers' needs (Lemos et al., 2018; Porter and Dessai, 2017). This scholarship calls for improving the level and quality of co-production interactions by using 'boundary spanners', i.e. individuals who mediate and manage the interactions (or boundary) between scientists and decision-makers (Cash et al., 2003; Kirchhoff et al., 2013b; Porter and Dessai, 2017; Safford et al., 2017). Yet, there is no clarity on what constitutes 'good-quality' interactions, or on the types of scientist-decision-maker engagement processes, that result in effective two-way translations to create usable science (Lemos et al., 2018; Meadow et al., 2015; Porter and Dessai, 2017). Here we present a case of co-production (Project Hyperion) that led to the translation of resource managers' information needs into actionable climatic metrics for water management. We describe how the metrics evolved iteratively through a year-long effort, and identify the boundary spanning and engagement strategies that enabled shared understanding across professional communities to emerge. Finally, we showcase and characterize the metrics that were identified through this process.

2.2.2 *Case Study and Methods*

About the Case Study: Project Hyperion is a basic science research project that aims to advance climate modelling by evaluating regional climate datasets using decision-relevant metrics. The project applies the concept of co-production to bring together scientists from nine academic institutions with managers from twelve water agencies in four watersheds: Sacramento/San Joaquin, Upper Colorado, South Florida, and Susquehanna. In this paper, we focus on the co-production of decision-relevant metrics for water management in each of the study regions. From the water managers' perspective, these metrics quantitatively describe aspects of climatic phenomena that are directly related to practical management problems; changes in these quantities would necessitate shifts in water infrastructure planning and operations. From the scientists' perspective, these metrics provide a test of model fidelity for decision-relevant phenomena, and hence push model development and scientific inquiry in more use-inspired directions.

The Hyperion team comprised 20 atmospheric scientists, earth system scientists and hydrologists from nine academic institutions. The water managers represented 12 different agencies that manage water quality, water supply, stormwater management, flood control, and water infrastructure design in the four case study regions. These water managers had high levels of technical expertise in engineering, hydrology or other sciences, and were purposefully selected because of their interest in the initial project concept and their ability to dedicate time to the engagement efforts. Three boundary-spanners (including two of the authors), whose expertise spanned the physical and social sciences as well as the practice of climate adaptation planning, contributed to the facilitation and mediation of scientist-water manager discussions.

Types of engagements: To identify these metrics, several structured and open-ended engagement methods were used during the course of the project. Structured engagement methods included workshops, remote and in-person focus-group discussions, and quarterly project update calls. There were also several less-structured, informal conversations between scientists, managers, and boundary spanners over phone calls or emails. Approval from Lawrence Berkeley Lab's Human Subjects Committee - Institutional Review Board was obtained for key engagements. The timeline of key engagement activities, along with goals and milestones at each stage is presented below. Figure B. 1 in Appendix B provides a short illustration of the timeline.

Dec 2016: First kick-off workshop with the entire project team, where project goals and research plans were discussed and co-developed. Each water manager also discussed their watershed's key climate related challenges, their current use of hydroclimatic data and information gaps they currently faced.

Mar-Apr 2017: Four regional remote meetings were organized (one for each case study region) with scientists and water managers. During the discussions key climate-related issues and associated hydroclimatic phenomenon of relevance were identified. A handful of aspects of hydroclimatic phenomenon and decision-relevant metrics were also identified in subsequent calls/e-mail communications following up from the meeting.

May-Jun 2017: The boundary spanners made a series of phone calls to key scientists from each case study region, to seek feedback on the information collected so far. In this process, it became apparent that further translation of the hydroclimatic phenomena to unambiguous quantitative metrics was required.

Aug 2017: A combined project team meeting (with all the scientists and water managers from all case study regions) was organized, in which the boundary spanners presented the hierarchical framework explaining that more work is needed to get to decision-relevant metrics. Managers agreed that more refinement is valuable, and that they were willing to spend additional time in getting to detailed metrics. Additional aspects of hydroclimatic phenomenon and additional decision-relevant metrics were identified in the meeting.

Sep 2017: Two regional scientists' meetings were organized (one for California and Colorado, another for Susquehanna and Florida). Scientists were paired in groups of two. Each group was assigned a specific hydroclimatic phenomenon based on their broad areas of expertise, and given the task of identifying a menu of potential decision-relevant metrics for each aspect of hydroclimatic phenomenon that was previously identified by the water managers. They were also asked to list down specific questions that they had for the water managers (and that would be discussed in subsequent focus groups).

Nov 2017: Boundary spanners consolidated information from all previous calls, and organized four regional focus group discussions with scientists and water managers of that region. The list of metrics was discussed in depth - to clarify, refine, improve and add details. The discussions were structured to first seek the water managers' comments and opinions on each of the metrics one-by-one. After the managers had provided comments on each metric, scientists were called on to respond and ask for additional details or clarification for each metric. This resulted in a long list of decision-relevant metrics for each case study region being finalized.

Boundary spanning at and between each of the activities: Each of these activities was interspersed with several open-ended phone calls, or email conversations with individual water managers or scientists. There was boundary-spanning work during and in between each of these activities.

2.2.3 *Critical Elements of Boundary Spanning*

The primary functions of boundary spanners are mediation across epistemic divides and translation of jargon and assumptions among different actors (Cash et al., 2003; Cash and Borck, 2006; Meadow et al., 2015). The literature often discusses the challenges of translation and mediation when actors are resistant to crossing epistemic boundaries (Cash et al., 2003). In Hyperion, most of the water managers wanted to incorporate climate change information in their decisions, and most scientists were dedicated to developing decision-relevant science. This collective goodwill notwithstanding, substantial efforts were needed to mediate differences in incentives and priorities, and to facilitate the translation of managers' needs into quantitative metrics and scientific research questions.

The management of the scientist-manager boundary to arrive at actionable rainfall metrics illustrates these tensions. Some of the managers wanted information on Intensity Duration Frequency (IDF) curves for rainfall events to make flooding-related decisions. The scientists, based on their expertise and modelling capabilities, prioritized metrics such as frequency and intensity of specific storm events and their relationship to rainfall events. While these metrics were related to decision-relevant quantities, they were often one step ‘upstream’ (in both the hydrological and metaphorical senses) of what the water managers needed for detailed planning. The upstream metrics represented drivers of key phenomena of interest rather than the decision-relevant phenomena themselves. Recognising this tension, the group co-created a shared understanding of the term ‘metric’. We introduced a hierarchical framework that distinguished ‘decision-relevant’ from ‘upstream’ metrics, illustrating the overlaps and linkages between the two, and showing how both types of results fit within the project’s larger goals. With this explicit linking of metric-types, managers could better appreciate the scientists’ focus on upstream storm metrics for modelling the causal processes that could eventually make IDF predictions more accurate. Scientists saw why it was necessary to understand the metric of interest to managers, i.e. IDF curves, and how linking their storm metrics with IDF results added to the novelty and impact of their efforts.

A critical element of such efforts was the presence of a boundary spanner with domain expertise in climate modelling. The three boundary spanners had varying degrees of facilitation, social science, climate science and adaptation expertise. While the literature generically recognises the importance of ‘background and experience’ in the subject matter (Bednarek et al., 2016; Meadow et al., 2015; Safford et al., 2017), there is less appreciation of the levels of technical expertise required to execute techno-scientific translations (Bednarek et al., 2018). For our particular project, having a boundary spanner who was also a modeller proved essential for translating water managers’ needs into quantitative climatic metrics. Given the aims of Hyperion, many boundary-spanning functions towards the later stages of the project needed in-depth (and often painful) discussions on model parameters, types of simulations, decision-relevant thresholds, statistical measures of model skill, etc. (Figure 8). In hindsight, we believe that a boundary spanner with expertise in water management could have been equally beneficial and may have augmented our eventual list of metrics. Overall, we found that, depending on the nature of what is being co-produced, boundary spanners may need higher levels of domain expertise than is generally acknowledged in the literature.

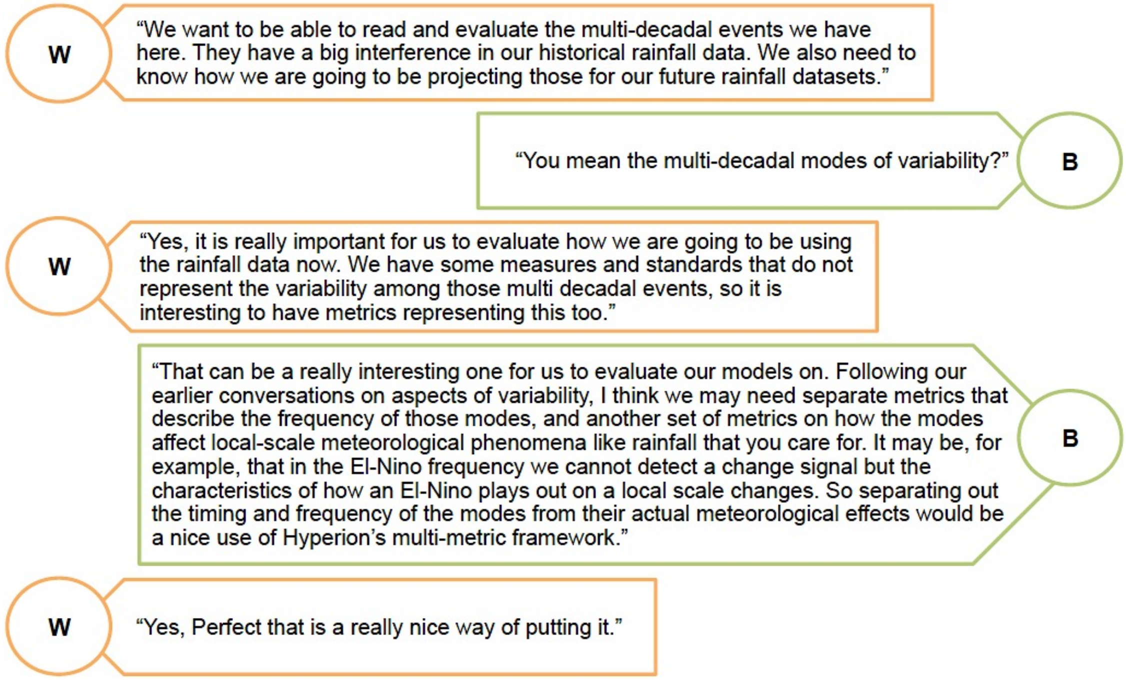

Figure 8: Dialogue between Water manager (W) and Boundary spanner (B). The figure presents a sample dialogue between the boundary spanner and a water manager that shows the benefits of having a modeller conduct the boundary-spanning function. The dialogue illustrates how the boundary spanner translated the water manager's narration of information needs into quantitative metrics that can be pursued by modelers.

2.2.4 *DIRECT AND INDIRECT APPROACHES TO THE MAKING OF METRICS:*

We approached the identification of metrics in both direct and indirect ways. The direct manner explicitly asked managers to identify any metrics for which they required projections. This approach implicitly assumes that decision-makers are able to articulate their knowledge in response to questions, and is a common premise in needs assessments (Hudlicka, 1996). While the direct approach was partially successful, it erroneously put the onus of metric identification solely on the water managers, who did not always know what to ask for or what the scientists had to offer by way of quantification. For example, the direct approach revealed water supply and floods as key climate related management issues in California, with snowpack, snowmelt, streamflow, dry spells and rainfall as hydroclimatic phenomena of interest. But managers were not always used to translating these phenomena into concrete parameters or thresholds (Briley et al., 2015; Hackenbruch et al., 2017).

We therefore supplemented the direct approach with an indirect approach that assumed that relevant knowledge cannot be revealed by direct questions, but needs to be extracted through more open-ended scenario analysis and contextual inquiry (Hudlicka, 1996; Zhang, 2007). Although such discussions are a time-intensive way to access internal knowledge structures (Hudlicka, 1996), combining direct and indirect conversational methods have been shown to be an effective way of eliciting user needs (Zhang, 2007). We relied on four indirect strategies that encouraged both scientists and managers to collaboratively identify decision-relevant metrics.

1. *Introducing hierarchical frameworks:* There was often confusion among scientists and managers on how specific a 'metric' needs to be to have an unambiguous interpretation from a modelling perspective. For example, 'peak streamflow' was suggested as a potential metric, but there were questions on what 'peak' meant to the decision-makers: was it daily maximum flow, or the high end of streamflow distribution, or values above certain thresholds? Hence we decided to re-define metrics through a hierarchical framework, starting from the management issue and ending with the metric (see also (Maraun et al., 2015)). In Hyperion, the hierarchy represented a logical framework that helped us to understand that peak streamflow, for instance, was an 'aspect' of a hydroclimatic phenomenon, and one step ahead of being an unambiguous metric (Figure 9).

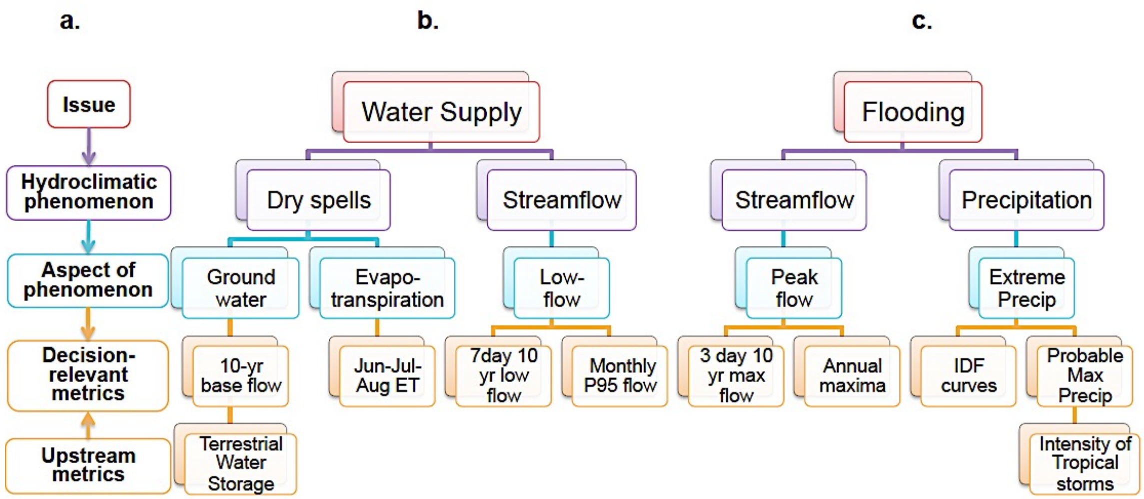

Figure 9: Hierarchical framework with examples. (a) illustrates the hierarchical framework starting from a management issue and ending in the metrics. (b) and (c) are examples of metrics and how they fit within the framework. The hierarchy starts with the 'Issue' or management challenge in the region (e.g. Flooding), and moves to the 'Hydroclimatic Phenomenon' related to the issue (e.g. Precipitation is a hydroclimatic phenomenon related to the issue of Flooding), and then to the 'Aspect of the Phenomenon' that is of specific interest for the management decision (e.g. Extreme precipitation is the aspect of precipitation that is of specific management interest). Finally, the hierarchy yields the actual 'Decision-relevant metric', which refers to a quantity that has potential use for the water managers and has an unambiguous formula or algorithm that can be applied to both observation-based data products and model outputs (e.g. Probable Maximum Precipitation (PMP) is a metric related to extreme precipitation). We also identified upstream metrics that describe phenomena hypothesized to be important drivers of the decision-relevant phenomena (e.g. Intensity of tropical storms of certain durations or return periods are an upstream driver of PMP).

2. *Discussing planning challenges regarding hydroclimatic phenomena:* The discussion of current and future planning challenges was a productive path towards metric identification. For example, when asked about planning goals with respect to streamflow quantity, some managers suggested that the aim was to have a full reservoir on July 1st. Through this exchange we identified cumulative run-off on July 1 as a decision-relevant metric. Another discussion centred on recent climate- or weather-related planning challenges in the managers' regions (such as Hurricane Irma, or the Oroville dam failure). One of the managers discussed an ice-jam related flooding event and described how warm temperatures and heavy rain conditions in

early spring caused the snow to melt rapidly, leading to flooding. This prompted a collective discussion about whether frequency of rain-on-snow events and the associated run-off could be an actionable metric to help anticipate and manage such events.

3. *Discussing new models, tools, or datasets:* One of the scientists described a new type of satellite data on terrestrial water storage (TWS) and its potential to aid in flood/drought prediction. Managers responded that their agencies primarily used 10-year ground water (GW) baseflow as a key metric for drought predictions, but that it was not easy to collect relevant data for computing GW baseflow. They were interested in alternatives to this metric and the scientist explained that new findings suggested that TWS (in some regions) can be a good predictor of GW flow. The co-production team collectively agreed that both TWS and 10-year GW baseflow would be good decision-relevant metrics, where TWS would be explored as a potential proxy to GW baseflow.
4. *Using analogies for 'good' metrics:* Some of the new metrics identified in our project came from discussions of other 'good' metrics. For example, one well-received set of metrics was visualised through the 'Snow Water Equivalent (SWE) triangle', which characterizes the annual cycle of snow accumulation and melt using a fitted triangle (Rhoades et al., 2018). The water managers thought this was a "nifty" group of metrics as they capture key dynamics of snow for management purposes. The popularity of these metrics led to discussions on whether a similar set of metrics describing the annual cycle of rainfall would also be useful. A new composite approach, which we are tentatively calling 'rainfall geometry' (to signify whatever geometric figure fits the annual cycle of rainfall), and which includes the start date of the wet season, peak rainfall, and length of the wet season, was co-developed as a promising multi-metric framework that captures decision-relevant rainfall metrics.

Overall, we found that the making of decision-relevant metrics needed an iteratively derived mix of direct and indirect engagement approaches to capture the information needs of the water managers and also to translate them into modelable metrics for the scientists (Figure 10).

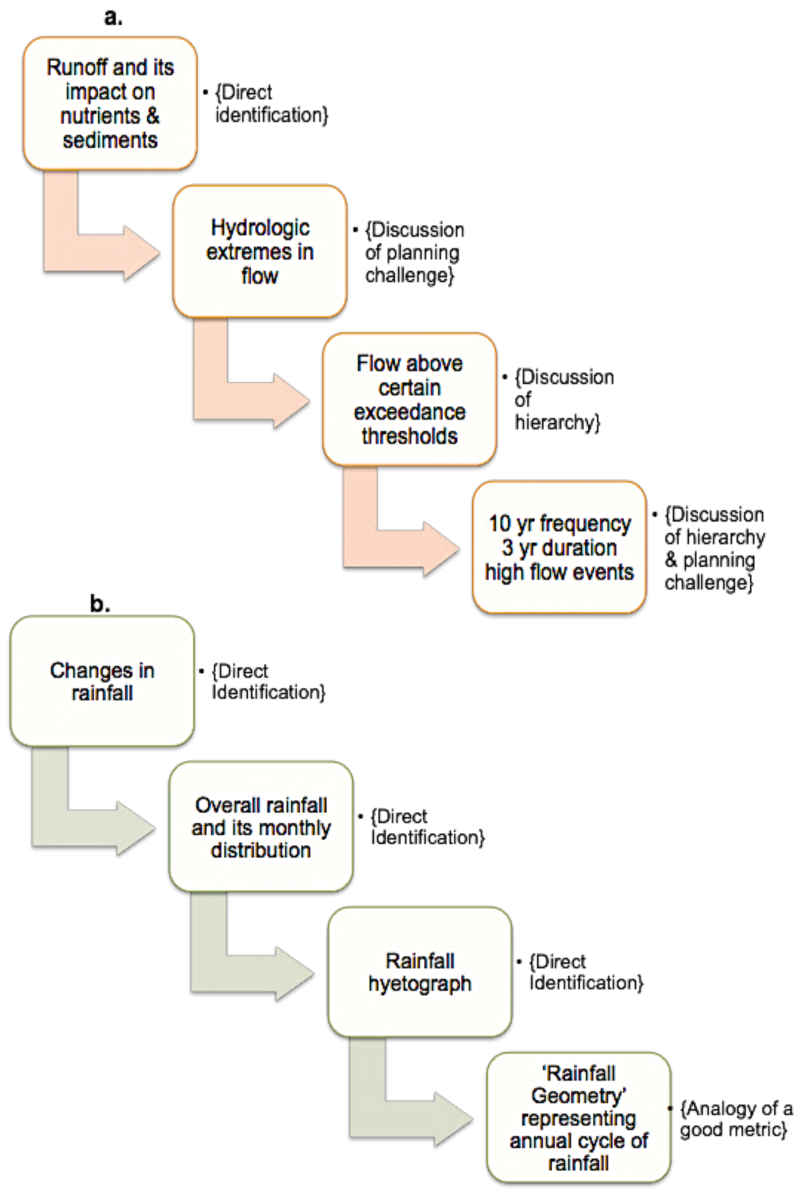

Figure 10: Examples showing the evolution of decision-relevant metrics. (a) and (b) show the making of two decision-relevant metrics, and the types of strategies at each stage that helped improve and refine them. (a) shows the evolution of the metric that represents the 3-year critical duration of October-March high flows at a 10-year recurrence interval. The initial direct identification gave a broad understanding of the importance of runoff for nutrients and sediments, and then a discussion of runoff-based planning led to identifying hydrologic extremes as one of the important components of runoff. Using the hierarchy (**Figure 9**), we came to understand that 'extremes' were an 'aspect of phenomenon', and we probed further to find that extremes actually meant flows above certain thresholds. We derived the final unambiguous metric at the next iteration where we interrogated the types of exceedance thresholds that impact water quality management in the region. (b) shows the making of a rainfall metric. First, the direct method highlighted that changes in rainfall patterns were an important challenge for the region. In the next 2 iterations, which also used direct engagements, we identified the specific aspects of rainfall that were of importance. Finally with the analogy of the 'good metrics' of the SWE triangle, we identified "Rainfall Geometry" as a promising concept for additional decision-relevant metrics.

2.2.5 *DECISION-RELEVANT METRICS AND THEIR CHARACTERISTICS:*

Table 3 presents examples of the metrics identified in the project (Table B. 1 in Appendix B has the full list for all four regions). In some cases, these metrics already existed in other contexts (such as in engineering or hydrology manuals), but had not been recognised as metrics relevant for climate modelling prior to the co-production process. We also observed that not every identified metric mapped onto a specific management decision. Some metrics, such as deviations from historical mean snowpack, were useful for better understanding the future state of watersheds rather than for making decisions. The interest in snowpack shows that there are overlaps between upstream and decision-relevant metrics; several water managers were, in fact, interested in understanding upstream processes in addition to working with actionable metrics (Vano et al., 2019). Finally, we found that the relevance of metrics depends on, and evolves with, the availability of climate information. In regions where there was limited availability of climate data, even simple climatic metrics such as monthly or annual run-off were considered relevant. In regions with more information, such simple metrics were not as useful; managers identified more detailed metrics, such as the runoff associated with highest snow melt rate, or maximum daily or 3-day flow volumes, as relevant. A detailed analysis of how and why the characteristics of decision-relevant metrics differed among the water management agencies is planned for the next phase of the project.

Region	**Issue**	**Hydroclimatic Phenomenon**	**Aspect of Phenomenon**	**Decision-relevant Metric**	**Decision/Use**
CA	Water Supply	Snowpack	Annual cycle of snow accumulation and melt	Snow Water Equivalent (SWE) triangle(Rhoades et al., 2018) - Peak snow (amount and timing), and its relationship with average snow-accumulation and -melt rates, and timing and length of accumulation and melt seasons	On-stream reservoir management, and understanding future streamflow characteristics. Shape of the triangle shows the changing dynamics of the snow season, and what to expect in terms of runoff timing and amounts.
CA	Flooding	Streamflow	Peakflow {Pulse events}	Frequency of Rain-on-snow events and magnitude of associated run-off	Reservoir operations and flood management.

CA	Water Supply	Snowpack	Inter-annual Variability in Snowpack	Deviations from historical mean in SWE, Snowpack and Snowmelt (amount and timing)	Multi-year water supply planning and drought preparedness.
CO	Water Supply	Streamflow	Seasonal Streamflow amount (in snowmelt season)	Cumulative run-off on July 1 and August 1	Annual water supply planning for the year done based on July 1 or August 1 reservoir level estimates (depending on the reservoir).
CO	Floods	Streamflow	Seasonal Streamflow amount (in snowmelt season)	% of average annual inflow for Apr-July	Reservoir management - this metric is an input into some reservoir operations models.
CO	Water Supply	Streamflow	Low-end Streamflow	7-day 10 year low flows	Water quality management (issuing discharge permits), and water supply planning during dry years (determining permit limits for water withdrawals).
FL	Floodi ng	Rainfall	Extreme Rainfall	Intensity Duration Frequency or IDF curves, specifically, 1-day, 3-day and up to 7-day rainfall events, for 10, 25, 50 and 100 year frequency intervals.	To calculate applicable discharge rates for different storm water management infrastructure. Design criteria used for drainage and flood protection are in terms of IDFs. In other words, designing of standard engineering practices for infrastructure.
FL	Floodi ng	Rainfall	Extreme Rainfall	Probable maximum precipitation**.** For 1-day, 3-day and maybe up to 7-day events	Large storage infrastructure design (like high dams).

FL	Water Supply	Rainfall	Variability in Rainfall	Rainfall anomalies at Monthly time scales	Water supply planning, and drought monitoring
SQ	Water Supply	Streamflow	Peakflow	10- year frequency 3-year duration high flows for Oct-March	Water quality management in terms of monitoring Chesapeake Bay water quality standards.
SQ	Floodi ng	Streamflow	Average/ cumulative flows	Mean annual flow and harmonic mean flow	Water supply planning, for monitoring passby flows and conservation releases associated with water withdrawal permits. Water quality management for calculating design flows for effluent limitations based on water quality criteria.
SQ	Water Supply	Streamflow	Low-end Streamflow	7-day10-year low flow	Water quality management in terms of wastewater assimilation standards for discharge permits. Water supply planning in terms of passby flows or conservation releases for water withdrawal permits.

Table 3: Examples of decision-relevant metrics. The table highlights a few of the key issues, hydroclimatic phenomena, aspect of phenomena and decision-relevant metrics for each region. 'CA' refers to Sacramento/San Joaquin, 'CO' is Upper Colorado, 'FL' is South Florida, and 'SQ' is Susquehanna. The last column also describes some of the potential decisions or uses for these metrics that were highlighted by the case study water managers.

2.2.6 *CONCLUSIONS*

In this paper we outline the process by which climate scientists and water managers (eventually) crossed the boundaries of both mandate and epistemology to co-produce decision-relevant metrics. To our knowledge, this is the first study to document in detail a list of actionable climatic metrics for adaptive water management, and the co-production processes needed to develop such metrics. Our work confirms the importance, and also complexity, of identifying decision-relevant climatic metrics. We found that the onus for this task lies not just with the decision-makers, but equally with the scientists, for translating user needs into quantitative model-friendly metrics. In addition, we found that the commonly used direct approach to identifying decision-makers' information needs was insufficient for this task. A judicious mix of direct and indirect approaches was needed to “make” these metrics. Key indirect strategies included introducing a hierarchical framework linking management issues with actionable metrics and upstream phenomena; discussing metrics specifically in light of planning challenges; discussing new models, datasets and scientific findings that managers did not yet know; and using analogies of good metrics from other hydroclimate phenomena. Eventually, the twin functions of the metrics (of guiding decision-relevance and extending model capability) spoke to both the decision-makers’ and the scientists’ priorities, and allowed both groups to co-exist within the project. Additionally, the domain expertise of the boundary spanner, an under-appreciated phenomenon in the co-production literature, proved to be crucial for effective trans-boundary translation.

Although time-consuming, the richness of our understanding came from these iterative back-and-forth engagements, where even the processes that did not fully work were essential to get to the processes that did work. The final result of our efforts, i.e. the list of co-produced decision-relevant metrics, serves as a significant product for both climate scientists and water managers. Co-production is potentially transformative but time- and resource-intensive (Briley et al., 2015); we hope that insights from our experience can assist other projects to move their practices of co-production forward more efficiently.

3. ADAPTATION 'READINESS' OF CLIMATE MODELS AND DATASETS

The previous chapter identifies the types of scientific information that decision-makers need to make adaptation decisions. Following this, Chapter 3 examines whether current climate science is able to credibly provide the information that decision-makers require. In this chapter, I evaluate how well climate models are able to predict decision-relevant climatic metrics (using the case of the decision-relevant metric of chill hours). This chapter also provides decision-makers with guidance on selecting the most appropriate climate models and datasets for their specific adaptation context. Overall, this analysis sheds light on whether current climate models and datasets are 'ready' to inform adaptation efforts. This chapter is currently under review for a journal publication, and has been included here with the permission of my co-authors Dr. Andrew Jones and Dr. Amber Kerr. I led the design, data collection, coding, and analysis for this project with advice and support from Dr. Jones. The manuscript was developed in collaboration with Dr. Jones and Dr. Kerr.

3.1.1 *INTRODUCTION*

The past decade has seen a large proliferation of different climate projections. The Coupled Model Intercomparison Project (CMIP5) involves over 25 modeling centers across the world, and currently there are about 60 General Circulation Models (GCMs) that can provide projections of future climate at broad spatial scales (WCRP, 2017). Further, there exist various downscaling methods that can derive local- or regional-scale projections from the larger-scale GCM data, resulting in different types of downscaled datasets. For decision-makers such as adaptation practitioners, farm managers/advisors, and water managers looking to use climate information for future planning, this gives rise to what Barsugli et al. (2013) term the 'practitioner's dilemma' of how to choose the right projections for a particular context.

One of the most common questions from climate information users is how many projections and which climate models they should use in their assessments (Maurer et al., 2014; Snover et al., 2013). The goal is to pick a subset of GCMs that is small enough to ensure the data is manageable, yet large enough to capture a meaningful range of possible future outcomes. Currently, the most established way of picking GCMs is through historical evaluation of skill (Kundzewicz and Stakhiv, 2010). This involves comparing model simulations to historical observations of certain climate metrics to identify particular sets of models that perform well in simulating the processes of interest (Barsugli et al., 2013). However, most studies evaluate model skill for metrics of broad physical climate phenomena (e.g. large-scale atmospheric patterns and averages/extremes in temperature and precipitation), and very few explicitly focus on specific decision-relevant metrics associated with particular adaptation decisions (e.g. growing degree days[7] and chill hours[8] in the agriculture sector, or heating or cooling degree days in the

[7] Refers to the number of degrees by which daily average temperature falls above a threshold temperature.

energy sector). Since climate models predict different metrics with varying skill (Girvetz et al., 2013; Snover et al., 2013), the relationship between the skill of broader physical climate metrics versus decision-relevant metrics[9] may not be straightforward, making selection of GCMs quite challenging.

Once model skill has been evaluated, there is still a question of how many and which models to pick based on the results of the evaluation. This selection of the appropriate subset of models is a complicated issue (Mote et al., 2011). Some researchers suggest that excluding the least realistic models for the region from historical evaluation of skill can reduce the uncertainty in future projections (McSweeney et al., 2014; Walsh et al., 2008), while others suggest that broadly any 10-14 randomly chosen GCMs should be able to provide an estimate of the future that is as robust as the results from the 'good models'(Maurer et al., 2014; Mote et al., 2011; Pierce et al., 2009). Further, some others recommend picking a smaller subset of the 'good models' that substantially cover the range of projections of all the good models, so that the amount of data is manageable for the user (Pierce et al., 2016). Despite these varied opinions on model choice, few authors have assessed the implications of GCM choice and skill for projections of decision-relevant climatic metrics.

The goal of this paper is to examine how model selection impacts projections for decision-relevant metrics, and to highlight the similarities and differences in results based on whether models are chosen for skill in broad-scale physical climatic metrics or for skill in specific decision-relevant metrics. Using chill hours at a specific location (Fresno, CA) as our case study, we first evaluate the skill of different GCM-derived datasets (both downscaled and raw data) in predicting historical chill hours. We then explore whether models with good skill for broad physical climatic metrics in California are also skilled in predicting chill hours in Fresno, and we investigate whether and to what extent projections of the future differ based on skill-based model selection.

3.1.2 *CHILL HOURS IN FRESNO, CALIFORNIA AS THE CASE STUDY*

Chill hours (defined as cumulative hours below 7.2°C from November 1 to February 28 or 29) is one of the most important decision-relevant climate metrics for temperate fruit and nut tree crops. Many fruit and nut trees must meet a certain winter chilling requirement for the flowers and fruits to develop properly and for the trees to attain optimum yields (Luedeling et al., 2011). Reduced winter chill can have a significant negative impact on crop yield and quality, and sustained decline of chill hours may impact the viability of some perennial crops in areas where they were once widespread (Kerr et al., 2018; Lobell et al., 2006; Luedeling et al., 2009a; Medellín-Azuara et al., 2011; Pathak et al., 2018).

Historical observations of temperature data in the Central Valley of California, a major center of fruit and nut production, have shown that chill hours are declining at a rate of -6

---

[8] Calculated as the cumulative sum of hours below a stated base temperature

[9] Decision-relevant metrics are often computed using specialized algorithms for which physical climate metrics serve as inputs. While we make a distinction between 'physical climate metrics' and 'decision-relevant metrics' in this paper, we also acknowledge that there may be some overlap between the two. For example, some basic physical climate metrics such as monthly average temperature or seasonal precipitation patterns can also be decision-relevant metrics.

to -20 hours/year (Baldocchi and Wong, 2007). Orchard crop advisors from University of California Cooperative Extension, as well as farmers themselves, have reported observations of lower chill hours in the last decade and associated negative impacts such as uneven harvest, poor fruit or nut set, and reduced yields (Doll, 2013; Doll and Beede, 2016; Hinckle, 2015). Adaptation measures such as orchard microclimate management and chemical applications to break dormancy might have the potential to alleviate some of the negative impacts of winter chill reduction in the short-term (Luedeling et al., 2009a). However, such adjustments often entail substantial costs (Luedeling, 2012); therefore, estimates of future chill could help growers better anticipate and prepare for additional management costs. In addition, forecasting long-term trends can help to choose the right crop species, varieties, or rootstocks, based on projected future chill hours for the region (Lobell and Field, 2011; Luedeling et al., 2009a).

While not all adaptation decisions require detailed projections of future climate, on-farm adaptation decisions such as those identified above require very specific types of information. For instance, farmers, farm advisors or policymakers may want to know: What particular crops are at risk in a specific region? What are optimal chill thresholds for ‘low-chill’ cultivars of crops? To what extent can on-farm temperature management methods overcome the reduction in chill? All these questions require models that are able to accurately predict decision-relevant metrics at local scales, and hence choosing appropriate models is an important consideration for projections to be relevant to farm-level decision-making. However, the two key studies on chill hour projections in California (Baldocchi and Wong, 2007; Luedeling et al., 2009a) use only a few of the currently available GCMs. While these studies acknowledge that chill hour projections may differ substantially among different GCMs, a critical examination of the impact of model choice was outside of their scope. Therefore, it is not clear whether their results represent the full range of potential projections of the future, and whether culling the least-skilled models for chill hours could narrow the uncertainty range in their future estimates.

Most model choice recommendations for the Western US are based on model skill evaluations of broader physical climatic metrics, such as seasonal minimum or monthly mean temperatures, monthly or seasonal maximum precipitation, correlation with El Niño tele-connections, etc. (Brekke et al., 2008; CCTAG, 2015; Pierce et al., 2009; Rupp et al., 2013). Specifically for impact and adaptation studies in California, the state’s Climate Action Team – Research Working Group recommends using a subset of 10 models that have been identified by the California Department of Water Resources (DWR) as models that provide reasonably realistic simulations of the state’s climate (Cal-Adapt, 2017; CATRWG, 2017; CCTAG, 2015). For cases where using output from 10 models is unwieldy, this team recommends using a further-reduced set of 4 models that substantially cover the range of variability from the set of 10. However, it is not immediately obvious whether this set of 10 (or 4) models that have good skill scores for broader physical climatic metrics will also predict decision-relevant metrics (such as winter chill hours) with similar accuracy.

With this background and context, this study aims to assess model skill in predicting chill hours and examine whether the choice of GCMs alters the results of chill hour projections. While our paper focuses on the California context, this comparison of broad versus specific skill in climate metrics could also provide useful insights to a larger set of climate information users who are interested in evaluating future impacts of decision-relevant metrics.

3.1.3 *METHODS*

3.1.3.1 CALCULATION OF OBSERVED CHILL HOURS

In order to evaluate the implications of model choice for chill hours, we first analyzed long-term historical trends in observed annual chill hours for the Fresno station of the National Weather Service Cooperative Network (lat/lon: 36.78000, -119.71944). Fresno was chosen as the location of interest because the county is one of California's major production centers for fruit and nut crops such as almonds, grapes, pistachios, cherries and peaches (CDFA, 2016; County of Fresno, 2015). In addition, the Fresno weather station had a long record (1971-2012) of daily time-series temperature data, which is required for chill hour computation.

For this paper, we computed chill hours as the cumulative number of hours between 0 and 7.22 °C (32 and 45°F) in the winter months of November, December, January and February (Baldocchi and Wong, 2007). This is known as the Chilling Hours model. Though there are several different methods of computing chilling requirements for fruit and nut trees, the Chilling Hours model is the simplest and most transparent, and it is widely used by practitioners. Other studies have noted that different chill calculation methods (such as the Dynamic model, the Utah model, and the Positive Utah model) may yield different predictions for how chill hours will change in future climate (Darbyshire et al., 2011; Luedeling et al., 2009b). However, since the results of our paper rely mainly on a comparison between the observed and modeled chill hours, we limited the scope of this project to using one consistent chill hour calculation method while evaluating multiple GCMs. Although some specific results may differ, we anticipate that our broad findings and discussion points will be relevant to other chill hour models, which we hope will be tested by other researchers.

Since hourly data is not available for most GCMs, we used daily minimum and average temperature to estimate daily chill hours, following the trigonometric approximation method using an idealized mean diurnal temperature course, developed by Baldocchi & Wong, 2007. These authors found that their daily-to-hourly interpolation produced fairly accurate and unbiased chill hour estimates for this region (e.g., for Zamora, CA, the correlation between chill hours computed from actual hourly data versus interpolated daily data was $R^2 = 0.887$). Further, a comparison of chill hours from actual hourly data from the Fresno weather station versus the trigonometrically interpolated daily data show that the two methods provide very similar results ($R^2 = 0.98$) for both mean and slope of historical chill hours. Details of the trigonometric approach and the equations used are provided in Figure C. 1 and Equation C.1 of Appendix C.

To understand our chosen location within the larger regional context, we also computed chill hours for all other weather stations that are located within 75 km of the Fresno station and that have a comparable long-term temperature record. Five other NWS coop weather stations matched these criteria: Madera, Friant, Hanford, Lemoore and Visalia.

3.1.3.2 MODEL SKILL EVALUATION

For the model skill evaluation, we compared both downscaled and raw GCM data with observed historical chill hours for Fresno. Here we note that while the analysis of downscaled data can tell us how well this dataset is able to capture chill hours in Fresno, the results would not provide a true measure of quality of the GCM. This is because downscaled data from all GCMs are bias-corrected to the same observed dataset, thereby making several aspects of the GCMs statistically indistinguishable (Maurer et al., 2014). Hence, in addition to downscaled data, we also assessed raw GCM data to evaluate the skill of different GCMs in predicting chill hours.

We used raw climate model data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archives. For the downscaled dataset, we used the high-resolution data (1/16° or about 6 km spatial resolution and daily time-scale) derived using the Localized Climate Analogues or LOCA method, since the LOCA data is regarded as one of the better datasets for representing California's climate (Pierce et al., 2016). In addition, we assessed a third simple bias-corrected dataset, which we developed from the raw GCMs (detailed in Section 3.1.3.3). Temperature data for the grid cell containing the Fresno weather station was collected from raw and downscaled CMIP5 models (and corresponding ensemble members) for which daily average and minimum near-surface air temperature (T_{av} and T_{min}) outputs were available for both the historical run and the Representative Concentration Pathway (RCP) 8.5 future projections[10]. The historical runs begin in 1850 and end in 2005 and are driven by standardized greenhouse gas concentrations, aerosol, and land-use change forcing datasets. We chose RCP 8.5 in order to use projections with the largest potential signal compared to internal variability (McSweeney et al., 2014). We also note that choice of RCP is not expected to greatly influence model results for relatively near-term projections such as 2050 (CATRWG, 2017; Hawkins and Sutton, 2009).

We assessed downscaled data from a total of 32 GCMs and raw data from 29 GCMs. Wherever available, data from different initial-condition ensemble runs (model runs beginning with different initial conditions in 1850) of the GCMs were also included. For the downscaled dataset, only one ensemble run was available for each GCM. For the raw data, eight GCMs had daily time-series data for more than one ensemble run, while the remaining 21 only had daily data for a single run of the model. We identified a total of 57 model runs from the raw GCM dataset for further analysis (henceforth termed as 'raw GCMs' dataset), and 32 model runs from the downscaled dataset (or 'LOCA' dataset) (Table C. 1 and Table C. 2, Appendix C). Further, the 57 raw GCM runs were bias-corrected using a simple linear correction to provide a third dataset termed as 'Bias-corrected GCMs' dataset (exact method detailed in Section 3.1.3.3). Out of these model runs, 26 runs were common to all three datasets. That is, for 26 models, raw, LOCA downscaled, and simple bias-corrected data was available for the same ensemble run, allowing for one-to-one comparison between the three datasets.

Two evaluation criteria were used to assess model skill for computing chill hours: (a) comparison between modeled and observed multi-year mean annual chill hours for the

[10] RCP 8.5 represents a high pathway for future greenhouse gas emissions for which radiative forcing reaches greater than 8.5 Wm^{-2} by 2100 and continues to rise (IPCC, 2013b).

historical period of 1971-2012; and (b) comparison between modeled and observed slope/trend in chill hours (1971-2012). We chose these two criteria because, if models are to be used to project the future effect of climate change, it is crucial to test not only their ability to capture the mean state but also the historical trend (i.e. slope of chill hours), the latter of which indicates the models' historical response to climate forcing. Also, depending on the choice of method, both mean and slope of chill hours can be relevant for computing future chill hours from climate model data. For example, future chill hours can be obtained directly by taking the mean annual value from the climate models for the period under consideration. Alternately, future chill hours for the period can also be computed by taking a future slope estimate from the climate models and using it to extrapolate the current observed baseline mean (Daniels et al., 2012; Hawkins et al., 2013). Here, we also note that the mean annual chill hours and slope of chill hours are related metrics, and not fully independent of each other.

The comparison between modeled and observed data was conducted by using p-values from a Student's t-test comparing the observed results to the modeled outcomes obtained for the different model runs. The p-value provides a means of identifying which model runs differ from observations in a statistically significant manner. In this case, a model with a low p-value can be said to be definitely unskillful; i.e., the modeled and observed results differ significantly. However, a high p-value does not guarantee skillful performance of the model. A high p-value can also reflect a noisy observational signal or a high degree of variability in the model, either of which may make it difficult to reject the null hypothesis that the modeled and observational data in fact reflect the same distribution.

3.1.3.3 Bias Correction

Since the paper compares raw GCM output with a single weather station observation, the modeled values are expected to show some biases. The reasons for such biases could include systematic model errors as well as spatial averaging within grid cells (Teutschbein and Seibert, 2012). Downscaled data such as the LOCA dataset can potentially correct for some of these biases, depending on the types of corrections and the parameters for which corrections have been applied. LOCA employs a complex downscaling algorithm using a multi-scale spatial matching scheme to pick appropriate analog days from observations, along with a bias correction based on quantile mapping to ensure consistency with observed historical spatial patterns (Pierce et al., 2014)[11]. In addition to this LOCA dataset, we created a third 'Bias-corrected GCMs' dataset, by conducting a basic linear-scaling bias correction on the raw GCM data for monthly average and minimum temperatures (see next paragraph). We then compared this bias-corrected GCM data with the LOCA data in order to disentangle how such a monthly bias correction may affect GCM predictions independently of other aspects of LOCA downscaling. This allowed us to examine the implications of such biases on model skill and future projections.

The linear-scaling approach we use, calculates monthly correction values based on the difference between observed and modeled values (Teutschbein and Seibert, 2012). Since

[11] Further details of the methods used by LOCA can be found in Pierce et al. 2014.

this paper computes chill hours based on average and minimum temperatures in the winter months, the model outputs were bias-corrected such that the historical monthly multi-year mean temperatures (for the period 1971 to 2012) for the months of November, December, January and February are aligned with the observed values. This standard monthly correction allowed the models to retain their daily distribution patterns, while at the same time adjusting for mean biases at the monthly scale. We computed monthly correction factors for each of the model runs. These factors were added to daily T_{av} and T_{min} values to get corresponding bias-corrected daily temperature values for both historical and future temperatures. Detailed equations for the bias correction are provided in Equation C.2 of Appendix C. As with most bias correction methods currently used, the correction factors used in this paper are assumed to be stationary with time, i.e., they remain constant for all time periods.

3.1.4 *Results*

3.1.4.1 Observed Historical Chill Hours Show a Negative Trend Over Time

Figure 11 shows annual chill hours from 1971 to 2012 from the 6 weather stations. The multi-year mean annual chill for the historical period ranged from 900-1040 chill hours (ch) for the different stations. For this 41-year time period, a statistically significant negative trend in chill hours (at 95% confidence) was observed in all locations. The trend ranged from -6 to -8 chill hours per year (ch/yr). The data exhibited significant variability at annual to decadal scales, and hence shorter time intervals did not always demonstrate a statistically significant decline in chill. This suggests that the negative trend in chill hours is somewhat masked by internal variability (due to natural internal processes within the climate system), and while the observed multi-decadal trend is consistent with climate change (higher temperatures leading to lower chill hours), it is difficult to determine the degree to which decadal-scale variability has enhanced or diminished the effect of climate change in our 41-year historical dataset.

To put the above results in a decision-making context, the fruit and nut crops of California require anywhere between 200-2000 ch annually for optimal yields. Most almond and pecan cultivars have a relatively low annual chilling requirement of 200-500 ch, whereas walnuts, plums, peaches, and nectarines require medium chill upwards of 650 ch, and many cultivars of cherries, pistachios, apples, and pears have a higher chill requirement of over 1000 ch (Baldocchi and Wong, 2007; UCANR, 2018). The observed data shows that in the last two decades, the Fresno region has seen an increase in the number of years with chill lower than 700 ch. We also cross-checked our chill hour estimates at these point locations with gridded observed data from an area of 2000km^2 around the Fresno region and found that the chill hour estimates from the grid cell were very similar to our point location estimates.

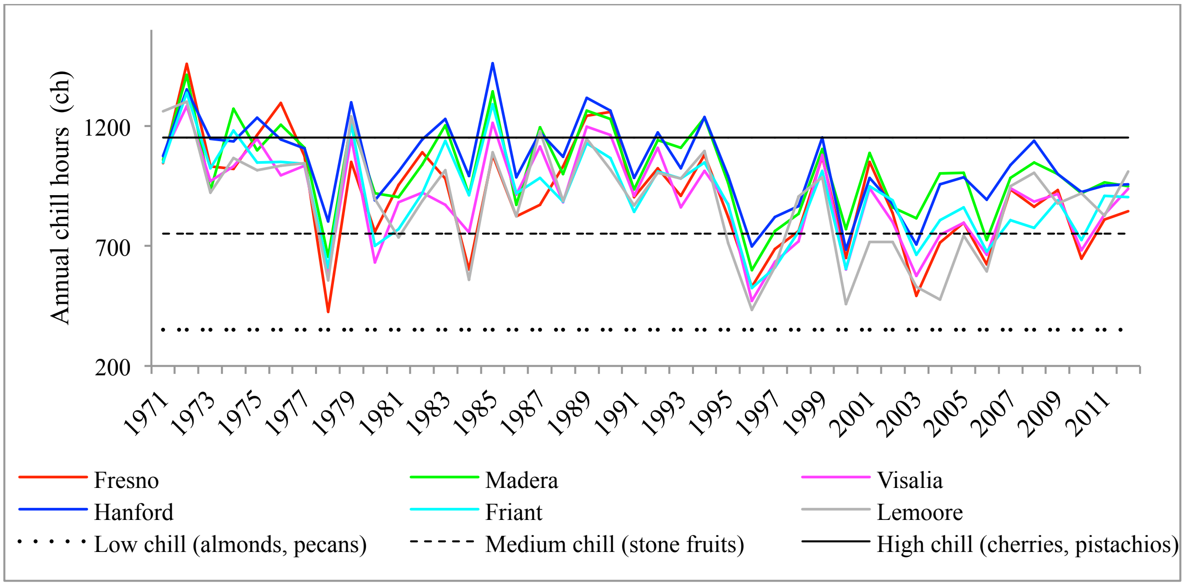

Figure 11: Observed annual chill hours for the historical period 1971-2012, computed from 6 weather station records in the vicinity of Fresno, CA. For reference, three annual chill hour thresholds are shown as straight lines. These are broad indications of thresholds, lower than which many varieties of the listed crops will be negatively impacted.

3.1.4.2 Model Skill Evaluation

Table 4 provides a summary of results from the historical skill evaluation conducted for the three climate model datasets: LOCA, Raw GCMs, and Bias-corrected GCMs.

	Annual Mean Chill Hours (ch)			*Chill Hours Slope (ch/yr)*		
Dataset type (below)	***# high-ranked model runs***	***Overall mean***	***High-ranked mean***	***# high-ranked model runs***	***Overall mean***	***High-ranked mean***
Observed	-	910	-	-	-8.4	-
LOCA	25 of 32	850	860	15 of 32	-1.9	-3.5
Raw GCMs	12 of 57	1290	950	42 of 57	-3.6	-5.3
Bias-corrected GCMs	47 of 57	840	860	46 of 57	-4.0	-5.1

Table 4: Summary of results from the comparison of model performance against historically observed chill hours from 1971-2012. Rows are the different types of datasets that were evaluated, and columns present results on model skill for annual mean and slope of historical chill hours. “High-ranked model runs” refers to the number of model runs that have a p-value of > 0.05. “Overall mean” refers to the mean prediction from all the model runs in the dataset (also referred to sometimes as “multi-model mean”). “High-ranked mean” refers to the mean prediction from only the high-ranked runs. The observed mean and slope are also provided for comparison.

3.1.4.2.1 LOCA Data Accurately Predicts Historical Mean but Underestimates Trend

The historical mean chill hour predictions from the LOCA downscaled dataset were largely accurate, with a majority of GCMs having p-values greater than 0.05, meaning that they were statistically indistinguishable from the observations. Since the inter-model variability in chill hours mean was not very high, higher p-values here represent models that predict historical mean chill hours close to the observed data from the Fresno station. The overall annual mean prediction from all model runs was 850 ch, which aligns fairly closely with the observed annual mean of 910 ch between 1971-2012. The spread in model predictions was low, with the highest annual estimate being 900 ch and the lowest 800 ch (Refer Figure C. 2, Appendix C). Mean chill hours from the high ranked LOCA model runs (i.e., with p-value greater than 0.05) was very similar to the overall mean, suggesting that model choice does not strongly influence prediction of historical mean chill hours from LOCA data. This result is unsurprising, as the downscaled data is designed to closely correspond to the observed data that provided the basis for LOCA bias correction.

On the other hand, the LOCA data systematically underestimated the significant negative slope that was observed in the historical period. Only 15 out of 32 model runs had a p-value greater than 0.05, and the slope prediction from the highest ranked model was only -5.8 ch/yr, with no LOCA model runs predicting a mean slope that was equal to or higher in magnitude than the observed mean slope of -8 ch/yr. The high-ranked model runs performed marginally better, with a mean slope of -3.5 ch/yr as compared to the overall mean slope of -1.9 ch/yr. Most model runs (23 of 32) predicted the mean historical slope to be lesser in magnitude than even the lower confidence interval of the observed slope (lower than -3.2 ch/yr), showing that the LOCA dataset systematically underestimated the historical slope of chill hours (Refer Figure C. 3, Appendix C).

3.1.4.2.2 Raw GCMs Tend to Overestimate Mean and Show Highly Variable Historical Trend Predictions

Because the LOCA data predicted chill hours trends that are systematically different from observations, this raises a question as to whether this bias originated in the GCMs themselves or in the downscaling process. Our skill evaluation of the raw GCMs provided insights into how the LOCA process transformed the raw model data. In contrast with the accurate historical mean predictions of the LOCA data, the overall annual mean prediction from all the model runs of the raw GCMs was 1290 ch, which is significantly higher than observed values (even in the coolest decades of our historical dataset). Only 4 of the 29 raw GCMs had model runs with a p-value greater than 0.05 (or 12 of 57 model runs) (Figure 12). The historical mean annual chill as predicted by these high-ranked model runs was 950 ch, which is more in line with the observed value of 910 ch. Only one model underestimated the mean, while 27 of 57 model runs predicted the mean as greater than the upper confidence interval of the observed annual chill hours (greater than 1350 ch). The intra-model variability in prediction of mean chill was not very high; different runs of a GCM gave similar results.

We note that the statistical correspondence between models and observations is not expected to be perfect even in the case of a hypothetical perfect model, because we are comparing larger GCM grid cells (of varying sizes and locations) to point observations. In particular, inclusion of nearby mountain ranges in the grid cell could explain the overestimation of chill hours in some cases. However, a closer examination of grid cell locations revealed that even the models that did not include the Sierra Nevada range also exhibited this overestimation. The grid cell locations of the 4 high-ranked models were also notably different, indicating that other model characteristics could be driving the chill hour predictions in addition to the size and location of the grid cells.

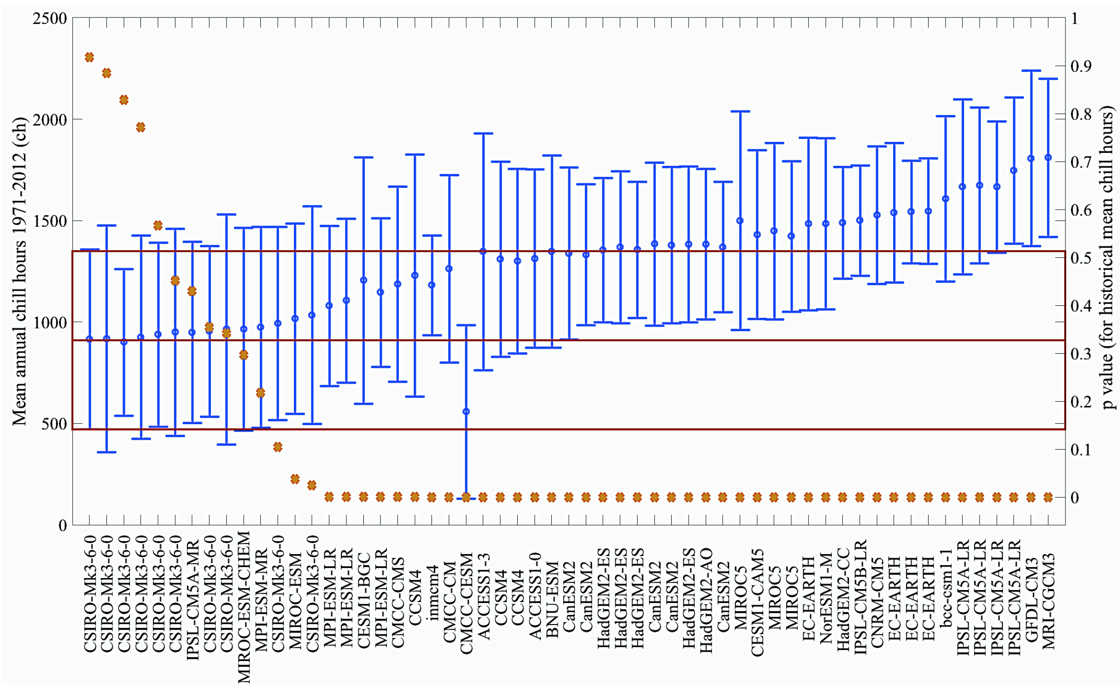

Figure 12: Statistical analysis comparing model performance to the historically observed mean annual chill hours from 1971-2012: On the X-axis, models are ranked by accuracy in predicting historical mean annual chill hours, with the best models on the left and worst on the right. The red box represents the range of the observed mean chill for the Fresno weather station (95% confidence interval). The blue dots represent the predicted historical mean annual chill hours from each GCM simulation, and the blue error bars are the standard error of the mean (95% confidence interval). The orange markers are the p-values (for mean chill hours) derived from Student's t-test comparing each GCM simulation to the observed data.

Figure 13 compares the observed historical slope in chill hours with simulated results. The results show that the raw GCMs predicted the slope of historically observed chill hours more accurately than the LOCA data, although both approaches tended to underestimate the magnitude of the slope. Although 42 out of 57 model runs had p-values greater than 0.05 (i.e., they could not be statistically distinguished from observations), the overall mean prediction of slope was only -3.6 ch/yr, which is less than half the magnitude of the observed chill slope (-8.4 ch/yr). Individual model runs had slopes ranging from -12.4 to +4.5 ch/yr, and 11 out of 57 model runs predicted an increasing trend in chill slope, while 6 runs predicted a decreasing slope as steeper than -6ch/yr.

The modeled results also exhibited high variability even within ensemble members of the same model, indicating that inter-annual to decadal scale internal variability plays a large role in slope predictions. For example, the slopes for the 10 runs of CSIRO-Mk3-6-0 ranged from -10.4 to +4.3 ch/yr, with one run ranked as the second best predictor of historical slope and another ranked as the second worst. Other models such as EC-EARTH and MIROC5 also showed high intra-model variability in prediction of slope. These results suggest that the prevalent inability of the p-value score to reject the null hypothesis could be due to the fact that the declining trend in chill hours may be strongly influenced by internal variability in the climate system in addition to forcing, making it difficult to discern true model skill for chill slope.

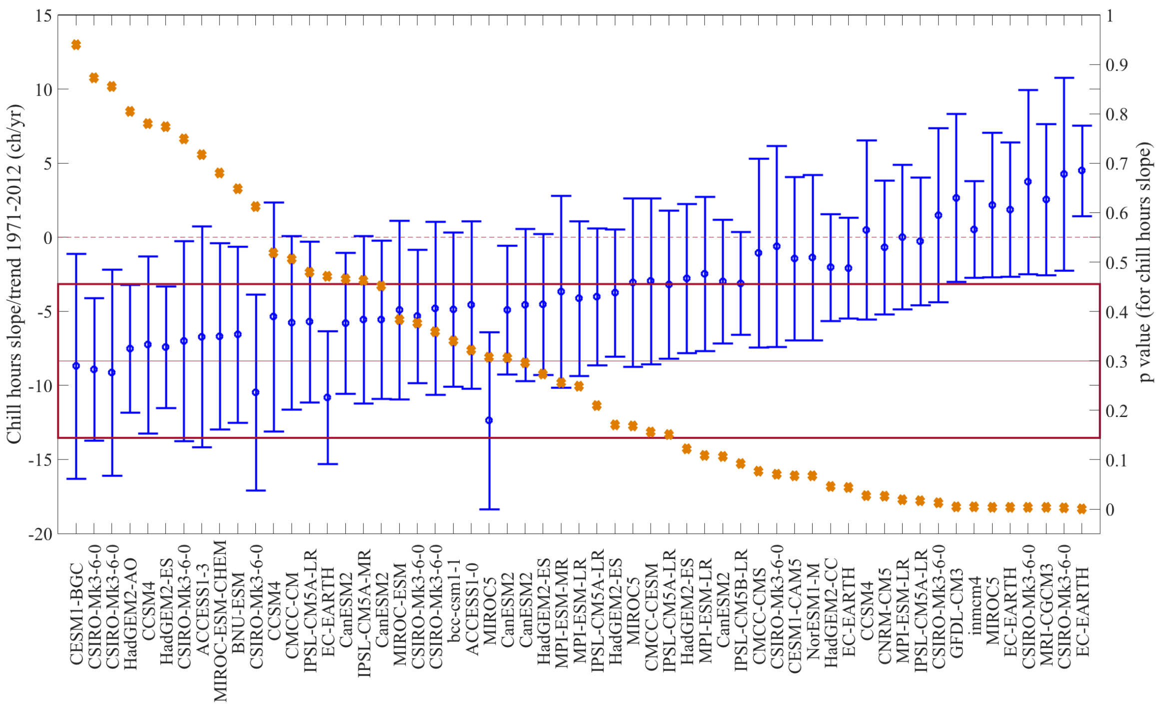

Figure 13: Statistical analysis comparing model performance to the historically observed chill hours slope from 1971-2012: On the X axis, models are ranked based on accuracy in predicting historical slope in chill hours, with the best models on the left and worst on the right. The red box represents the 95% confidence interval of the observed chill slope for the Fresno weather station. The red dashed line indicates 0 slope, i.e., no change in annual mean historical chill hours over time. The blue dots represent the mean chill hours slope from each GCM simulation, and the error bars represent the 95% confidence interval of the slope. The orange markers are the p-values for the slope derived from Student's t-test comparing each GCM simulation to the observed data.

Because raw GCM slopes were overall more accurate than LOCA slopes and showed a better distribution around the observed slope of -8.4 ch/yr, GCM performance did not explain the systematic underestimation of historical chill hours slope in the LOCA data. We further clarified this by comparing the GCMs to the LOCA data in a pairwise fashion, examining pre- and post- downscaling slopes for the same model runs (Figure 14). When we aggregated LOCA data for the same spatial area as the GCM grid cells, we found that these flat slopes were observed over the entire grid cell. This indicates that the systematic bias in the LOCA slopes most likely developed during the downscaling process and was not due to the scale difference between the GCMs and LOCA datasets. On the other hand, the LOCA downscaling was able to eliminate the cold bias in the model predictions of historical mean chill hours.

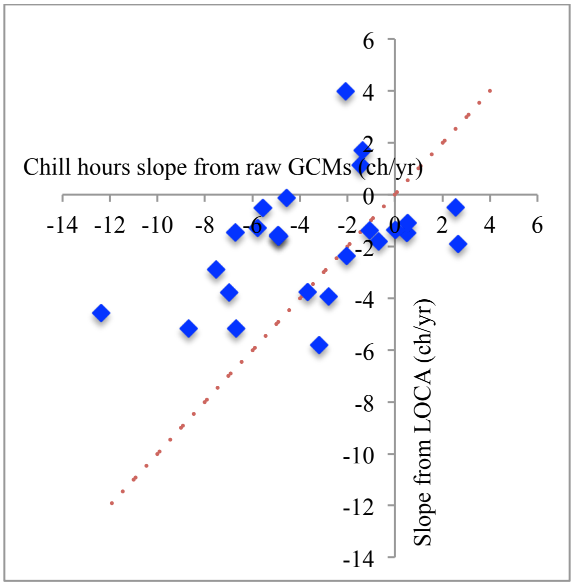

Figure 14: Pair-wise comparison between chill hours slope predictions from raw GCMs (X-axis), and from LOCA (Y-axis) illustrating pre- and post- downscaling slopes for the same model runs. Each of the blue diamond markers represents slope predictions from a single GCM run pre- and post- LOCA downscaling. The orange dotted line is presented as a reference linear line. The figure shows that the magnitude of the negative slope of the raw GCMs is systematically higher than the LOCA (i.e. more points are further to the top of the linear line than the bottom). The spread of the slopes is also larger for the raw GCMs than the LOCA slopes.

3.1.4.2.3 Linear Bias-Correction for GCMs Corrects Chill Hours Mean Without Changing Variability in Raw Slopes

Next, we evaluated the skill of our monthly temperature based bias-corrected dataset, to see how this simple bias-correction for the GCMs performed as compared to LOCA. Our simple bias correction was also able to eliminate the overestimation of mean chill of the raw GCMs. The corrected overall mean of 840 ch was close to the observed mean of 910 ch, and markedly different from the uncorrected multi-year mean of 1290 ch. Forty-seven out of 57 model runs had p-values greater than 0.05, and the mean from these high-skilled models was 860 ch.

In addition to correcting the mean chill hours as intended, bias correction impacted the slope of the estimated chill hours (Figure 15). Although the same incremental correction was applied to the temperatures for each year of a given model run, the non-linear nature of the chill hour metric means that the same absolute correction could either have a drastic effect on chill hours (e.g., if it shifts a large number of temperature data points from just below to above the 7.2 °C threshold) or a negligible effect (e.g., if all temperatures were above 7.2ºC both before and after correction). The non-linearity of the chill hour metric and its implications are explored in more detail in Figure C. 4, Appendix C.

Figure 15 shows that even among models with similar raw average annual chill, some models showed an increase in historical slope after correction while others experienced a decrease. Hence, the bias-corrected slopes displayed high intra and inter-model variability similar to that of the raw GCM slopes, with corrected slopes ranging from -10.8 to +3.1 ch/yr. The overall mean slope from the bias-corrected GCM runs was -4.0 ch/yr, which was very similar to the overall mean slopes from the raw GCMs (-3.6 ch/yr). When each individual model-ensemble was examined individually, we did not detect any specific pattern how the slopes changed with the correction.

We surmise that our simple bias correction was able to correct for overestimation in historical mean of the raw GCMs but does not change the intra- or inter-model variability of the historical slopes. Comparing these results to the LOCA dataset, we observe that both our simple bias-correction and the LOCA downscaling method are able to correct the mean chill hours, but they impact the chill hour slopes very differently. While the LOCA method systematically underestimates the historical slopes, our bias correction maintains a similar mean and variance in slopes as the raw GCMs.

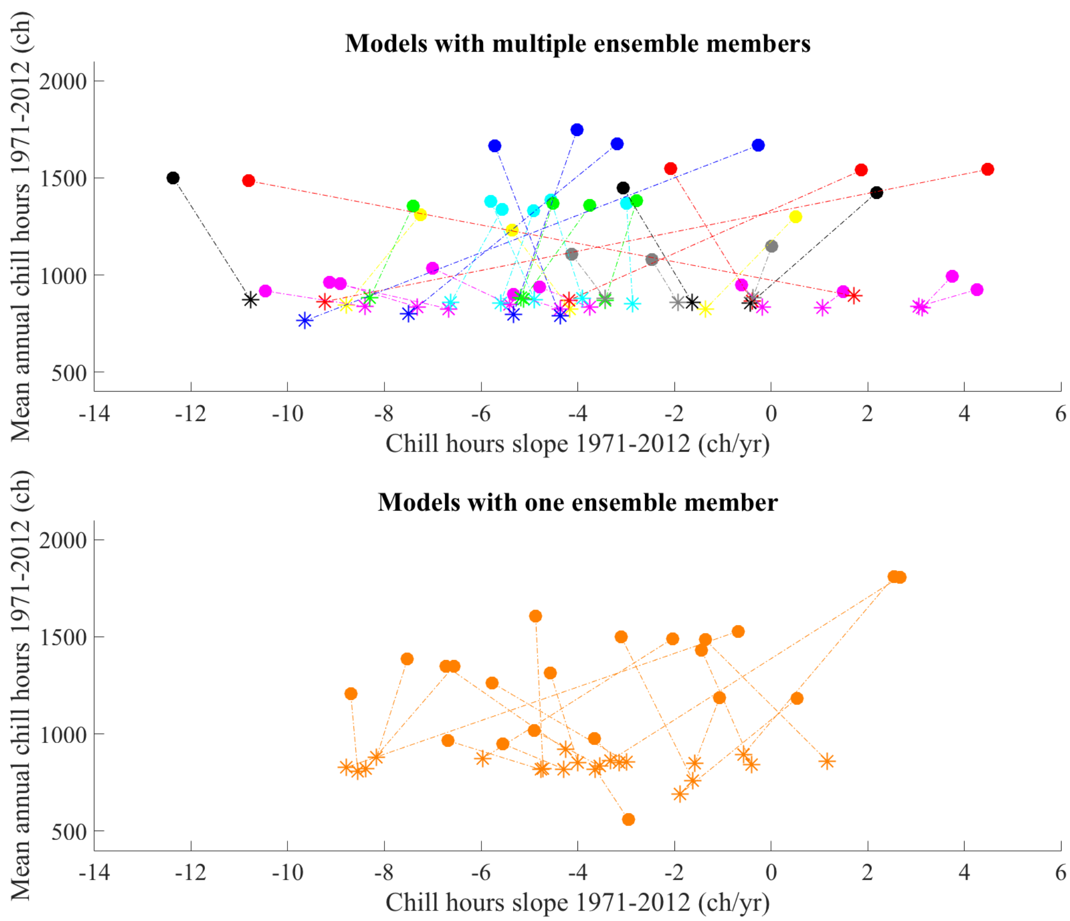

Figure 15: Scatter plots for historical chill hour slope (X-axis) and mean annual chill hours (Y-axis) from individual raw GCMs before bias correction (• circles) and after bias correction (* asterisks), with the leader lines showing the change. The top graph represents models that have multiple ensemble members, and each model is represented as a different color. The bottom graph shows the remaining GCMs (those with a single ensemble member). The results show that while the bias correction consistently reduced the

mean chill (i.e., asterisks are below circles), the change in slope after bias correction shows no specific pattern (i.e. the circles may move either left or right, even if they have similar mean chill before correction) and maitain similar variability as was observed in the raw GCM slopes.

3.1.4.2.4 Broad Skill versus Specific Skill of GCMs

The State of California has identified a subset of 10 and 4 models (henceforth termed 'CAL10' and 'CAL4' models) as good predictors of broad physical climatic metrics for California (such as seasonal temperature, precipitation, and El Niño teleconnections). However, our skill evaluation did not find these chosen models to be better skilled at predicting Fresno chill hours than the other GCMs. None of the raw CAL10 GCMs had a p value > 0.05 for predicting historical mean chill hours, and Figure 16 shows that the CAL10 and CAL4 models (the blue bar plots) do not systematically perform better at predicting historical mean or slope, as compared to the overall multi-model mean or the high-ranked models. While we understand that a direct comparison of these models and our results may not be possible due to differences in geographic and temporal scales in the studies, we nevertheless believe that it is useful to see how 'broad skill' (in terms of larger geographic scale and broader climatic metrics) may differ from 'specific skill' (at a local scale and for specific decision relevant metrics).

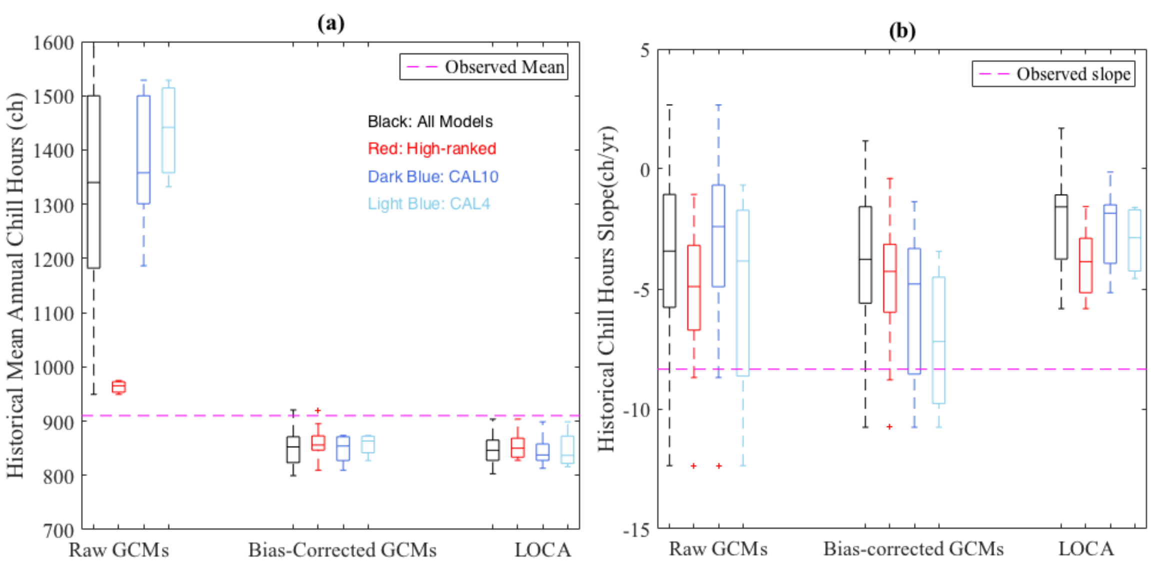

Figure 16: Historical mean chill hours and chill hours slope predictions from different model samplings. The figure shows that the models selected by the state of California (dark and light blue plots) do not perform better than the overall mean or the high-ranked models for chill hours, i.e., the predictions from the blue plots are no closer to the observed mean or slope (magenta dashed line) than the other model samplings (red and black plots). To avoid an uneven comparison, these box plots represent only those 26 model runs for which both raw GCM and LOCA data was available. Therefore, these results may be slightly different than the results in Sections 3.1.4.2.1, 3.1.4.2.2, and 3.1.4.2.3, which included all of the model runs evaluated in each dataset.

3.1.4.3 Future Projections of Chill Hours: Relevance of Model Skill and Choice

3.1.4.3.1 Overview of Future Projections from Different Datasets

Mean annual chill hour projections: We computed chill hour projections for three broad time periods: Short-term (2010-30), Medium-term (2010-50), and Long-term (2010-80) for the three different model datasets. In addition, we also computed projections for an illustrative case of the mid-century, which is detailed in Section 3.1.4.3.2 and Figure C. 2 in Appendix C shows the mean annual chill hours projections for the short, medium and long time-periods. Overall, we found that the raw GCMs which overestimated historical mean chill hours also provide much higher estimates of future chill hours for all time periods, i.e., the cold bias of the raw GCMs is carried forward into the future. The raw GCMs' overall mean projection of chill hours for the short- and medium-term time periods was even higher than the historical mean chill hours, which seems implausible. However, projections from the high-ranked raw GCMs were markedly different from the overall mean and more in line with projections from the other datasets, showing that model skill plays a critical role for projections from raw GCMs. The projections of mean chill hours from LOCA are slightly higher than the bias-corrected dataset for the future time periods. For both LOCA and bias-corrected datasets, the projections from the overall mean as well as the high-ranked models mean were very similar.

Slope projections: Firstly, we noted that all datasets predicted a declining trend in future chill hours, with the magnitude of the trend increasing as time progresses (Figure C. 4, Appendix C). The raw GCMs predicted a higher magnitude of the declining slope for the future than the other two datasets, and this difference was particularly significant in projections for later time periods, i.e., mid-century projections and beyond. The tendency of the raw GCMs to overestimate mean historical chill hours could be causing them to estimate a steeper future slope, because a higher estimate of present-day chill hours means a higher potential for decline in chill due to additional warming. Conversely, when the present-day mean chill hours are lower, there may be more days where chill hours are already closer to zero resulting in a smaller potential for decline in chill with time.

Overall, these results imply that it could be inaccurate to simply apply the raw GCMs' uncorrected future slopes relative to present-day chill observations (we explore this further in Section 3.1.4.3.2). We also found the LOCA slope projections to have a lower magnitude than the simple bias-corrected dataset. Considering that the LOCA projections of future mean chill hours were also higher, this indicates that the prevalent underestimation of historical slopes by the LOCA dataset is sustained into the future.

3.1.4.3.2 Difference in Projections Based on Model and Dataset Choice

The range of skills that we observed across models and the three datasets raised questions about the extent to which skill in predicting historical chill affects predictions of future chill. For a climate data user, there are several ways of getting to a projection of the future. These include a variety of choices in: selecting a dataset (raw or downscaled), choosing a sample of GCMs, and identifying a calculation method for obtaining future projections. Using the specific example of mid-century (2050) projections of chill hours, we highlight the similarities and differences in results based on these different choices. We illustrate our results using three climate model datasets, four model samplings, and two calculation methods for future projections. Table 5 describes each of these choices, and Figure 17 shows results for 2050 chill hours from the different sets of choices.

	Choices	Description
Climate Model Dataset	"Raw GCMs"	Dataset with the uncorrected GCMs.
	"Bias-corrected"	Dataset with GCMs that were bias-corrected using a simple linear monthly temperature correction.
	"LOCA"	Dataset with GCMs that were downscaled based on the Localized Climate Analogues method.
Model Sampling	"All models"	Refers to all of the GCMs (and model runs) within a particular dataset.
	"High-ranked"	Refers to only those GCM runs that had a p-value > 0.05 from the historical skill evaluation (where mean is used to compute chill, the p-value score for mean was used, and where slope is used the p-value for slope was used).
	"CAL10"	Refers to the 10 models identified by the State of California as having good predictions of California's climate.
	"CAL4"	Refers to the smaller subset of 4 models that encompass the range of projections that the CAL10 models produce.
Projection Calculation Method	"Direct mean" method	Refers to directly using the mean chill from the sample GCMs for the required time period. To avoid random errors due to use of a single year, we used the average annual chill from 2040 to 2050 as projections of 2050.
	"Slope" method	Refers to indirectly calculating future chill using a historical observed baseline of mean chill, and applying the chill slope (from sample GCMs) for the future period (i.e.) 2050 mean annual chill hours = Fresno observed mean annual chill hours 2001-2010 – (40 * chill slope 2010-50)

Table 5: Description of different climate datasets, model samplings and projection calculation methods that were used to illustrate the differences in future projections in chill hours due to model/dataset choice.

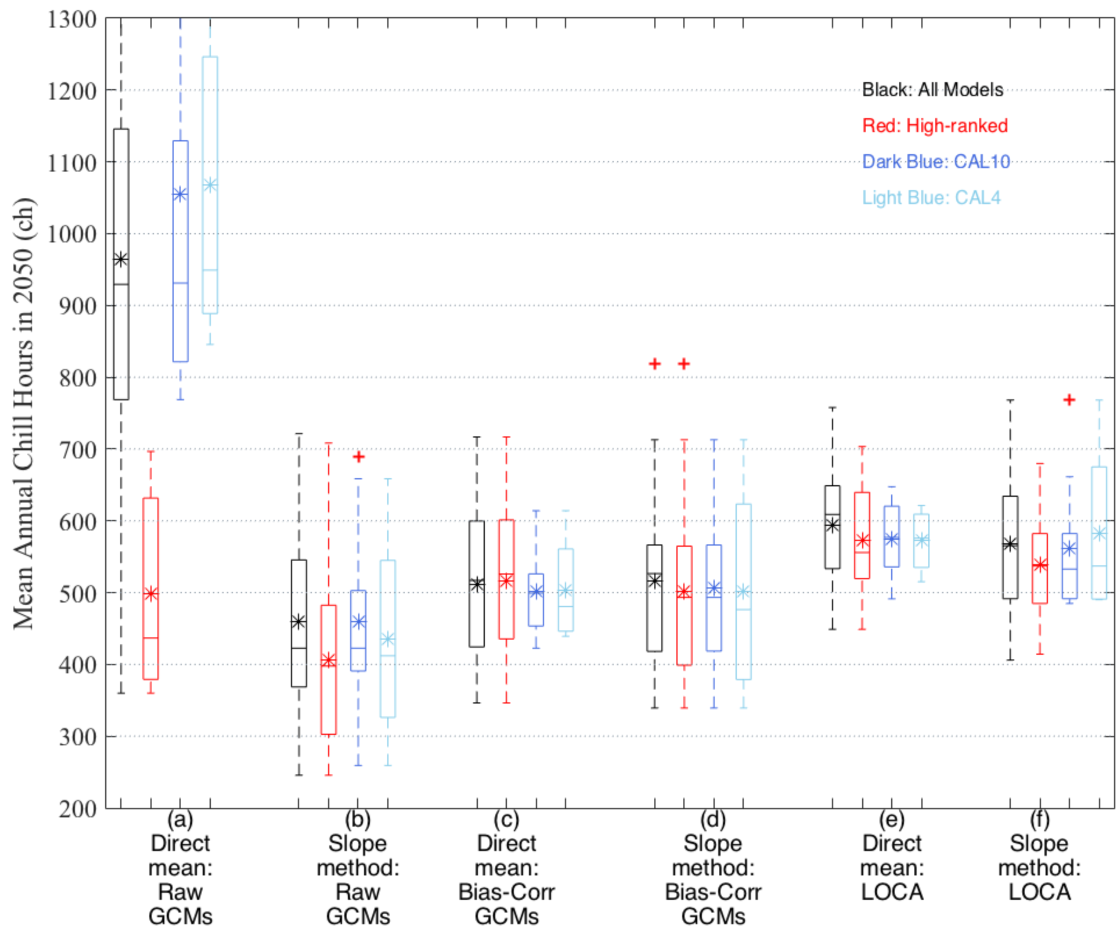

Figure 17: 2050 chill hours computed using different climate datasets, GCM samplings, and computation methods. Each cluster of box plots represents 2050 chill hours computed through one method (direct mean or slope method), and for one dataset (raw GCM, bias-corrected GCM, or LOCA). The asterisks show the mean values, and the red plus signs represent the outliers. To make the details legible, we chose a Y-axis limit of 1300 ch that excludes some of the more extreme results; the un-cropped version of the graph is in Appendix C, **Figure C. 5**. To avoid an uneven comparison, these box plots represent only those 26 model runs for which both raw GCM and LOCA data was available. Therefore these results may be slightly different than the results in Sections 4.2.1, 4.2.2, and 4.2.3, which included all of the model runs evaluated in each dataset.

Although it is unlikely that climate data users would choose to use raw GCM datasets directly, we explore projections from this dataset as it provides a means to assess the impact of model skill on future projections (see Section 3.1.3.2). Our results suggest that using the raw direct mean from all models, or the CAL10 and CAL4 models, provides the most unrealistic prediction method (Cluster a, Figure 17), as it implausibly claims that chill in 2050 will be higher than historically observed chill of 910 ch. The projections from the high-ranked raw GCMs fall within a more plausible range; they are lower than historically observed mean chill hours and are also more in line with estimates derived from the bias-corrected and LOCA datasets. On the other hand, future projections using raw chill slopes (Cluster b, Figure 17) leads to very low estimates of 2050 chill (compared to the two corrected datasets) for all GCM sampling scenarios. We suspect this may represent an underestimation of future chill, since we found that the magnitude of future uncorrected (raw) slopes tends to be higher than the corrected values (Section

3.1.4.3.1). If the bias-corrected dataset is used, the future projections are more consistent across different model choices. However, the projections from CAL10 and CAL4 models for the 'direct mean' method (Cluster c, Figure 17) do not capture the range of projections that the overall mean or the high-ranked models provide.

The LOCA dataset warranted close examination, as has been recommended by the State of California. It is evident from clusters e and f of Figure 10 that the LOCA dataset (irrespective of model choice) leads to higher projections of chill hours in 2050 (as compared to our simple bias-corrected dataset or the high-ranked raw GCMs). This reiterates that the historical underestimation of the negative slope by the LOCA dataset seems to be continuing into the future. It can also be observed that the CAL10 model sampling for LOCA (dark blue box plots in clusters e and f of Figure 17) does not capture the range of projections from the overall mean or the high-ranked models (black and red box plots in clusters e and f) for chill hours. Further, the CATRWG classifies the CAL4 models as HadGEM2-ES being the "warm/dry" model, CNRM-CM5 is "cool/wet", CanESM2 has projections in the "middle", and MIROC5 provides "complementary" projections or "covers a range of outputs" for certain broad physical climate metrics. However, we found that these classifications are not valid for the chill hours metric; for example, HadGEM2-ES was not the warmest model, and CanESM2 did not provide average projections of chill hours.

In summary, we find that raw GCMs either over- or under-estimate future chill hours (depending on the method of calculating future projections), unless the direct mean chill from high-ranked models is used. The underestimation of the negative trend in historical chill slopes by the LOCA dataset has resulted in higher mid-century projections for chill hours compared to the simple bias-corrected dataset and the high-ranked GCMs. Although it is difficult to know which of these results is most realistic, we do note that the underestimation of historical slope is most pronounced in the LOCA dataset. We also find that the CAL10 subset of models may not provide a complete range of possible future projections for chill hours as they do for broader physical climatic metrics. Hence, model choice has an important influence on analysis of future chill hours.

3.1.5 *DISCUSSION*

Our comparative analysis of projections from different datasets and model samplings for a decision-relevant metric, adds to the growing literature on model selection for adaptation studies. While we approach our study from the bottom up, evaluating model skill for a decision-relevant metric, most studies recommending models for adaptation studies have focused on a small set of broad physical climatic metrics. However, the non-linear nature of many decision-relevant metrics means that some physical errors may be amplified and others may be dampened. Chill hours only accumulate when temperature is below 7.2°C, which means there is a non-linear threshold relationship between temperature and chill hours (Figure C. 4, Appendix C). Therefore, it is not clear whether skill in broad physical climate is sufficient to ensure skill at decision-relevant scales.

In the previous section, we highlighted that the models identified as providing the most realistic representation for broad physical climatic metrics in California (CAL 10 models), do not necessarily have good skill in predicting this specific chill hour metric at a local scale. This could be because, although the evaluation process for the CAL10 models included performance metrics that were related to chill hours (such as some winter season temperature metrics), the evaluation was largely skewed towards other broad metrics such as precipitation extremes, heat waves, cold snaps, and ENSO patterns (CCTAG, 2015). While this selection is logical considering the importance of precipitation in California's climatology, many of these precipitation metrics are not as critical for analyzing chill hours. To explore a slightly more focused comparison, in this section, we discuss other key GCM assessments for the Western US that focus on physical climatic metrics that are more relevant to chill hours. We also compare and contrast our specific results with the recommendations about model choice from other GCM evaluations, and we discuss some potential reasons for these counterintuitive findings.

One of the most commonly accepted recommendations from broad-scale raw GCM evaluations for the Western US (as well as other global studies) is that the multi-model mean, rather than output from any specific model or models, is the best predictor for several temperature metrics including seasonal temperature metrics such as JFM (January-February-March) T_{min} , T_{av} and variability (Pierce et al., 2009), and monthly T_{av} (Rupp et al., 2013). Researchers have found that the multi-model mean leads to cancellation of offsetting errors in the individual global models. By contrast, our research finds that most raw GCMs have errors in the same direction for our metric of interest, leading to a systematic overestimation of mean chill hours (Section 3.1.4.2.2). Therefore, the multi-model raw GCM mean does not increase the accuracy of predictions of mean chill hours. While raw GCM output is rarely used to drive decisions at local scales, this analysis illustrates the complex relationship between skill for broad-scale metrics and specific skill at local scales.

We also identified a set of 7 models – from Rupp et al.'s (2013) model evaluation for the US Pacific Northwest – that ranked well (based on the authors' ranking criteria) for five broad temperature metrics that were most related to chill hours. These metrics were: mean annual temperature, diurnal temperature range (DTR) in December-January-February (DJF), trend in annual temperature, spatial standard deviation of the climatological mean DJF temperature, and spatial correlation of the observed to modeled climatological mean DJF temperature. However, we found no relationship between these 7 GCMs and the models that ranked well for the chill hour metrics in our analysis.

Despite clear differences between broad temperature skill and specific chill hour skill, our simple monthly T_{min} and T_{av} based bias-correction as well as the LOCA corrections were sufficient to correct for the overestimation of mean chill hours in raw GCMs. However, the LOCA dataset's equidistant quantile matching based bias-correction (Pierce et al., 2015) and analog days based downscaling (Pierce et al., 2014) led to a systematic underestimation of the negative trend in chill hours. That was not the case in our simple bias-corrected dataset. This contrast between the bias-corrected GCM dataset and the LOCA dataset was surprising, and our preliminary evaluation indicates that these lower slope predictions could be related to a fundamental issue of the LOCA data underestimating the warming trend of winter season (November-December-January-February) T_{min} and T_{av}, as compared to the trend observed in the raw GCMs (Refer

Figure C. 6, Appendix C). Although LOCA has been identified as a substantially improved downscaling method for California with better temporal correlations against observations (CCTAG, 2015) and better reproduction of summer maximum temperature and winter precipitation (Pierce et al., 2014), our analysis suggests that LOCA's skill for metrics most crucial for chill hours predictions (such as trends in winter season T_{min} and T_{av}) may need to be investigated further.

While the high internal variability in historical chill hours slope made it difficult to robustly identify overall 'good' models for slope, these results were still able to uncover some nuanced findings about implications of model selection for decision relevant metrics. We found that answers for questions on whether to cull models based on skill, and how many models to sample for robust projections, are not universally applicable and depend greatly on the metric and dataset under consideration. For example, in the case of the raw GCM dataset, culling models based on model skill provides a more accurate estimation of the past chill hours than the overall multi-model mean. On the other hand, projections from the LOCA dataset shows that even a sample of 10 models may not be sufficient to capture the range of potential future chill hour scenarios that are represented by the high-ranked models for chill hours.

Further, our results strongly suggest that practitioners who are looking to use the LOCA dataset for chill hour analyses in California should be aware that all models in the LOCA dataset systematically underestimated the historical declining trend in chill hours and showed a less severe decrease in future chill hours as compared to the other datasets. While it is difficult to assess whether LOCA projections are more or less realistic as compared to other datasets or downscaling methods, we think that it is important to note that irrespective of the number and types of models chosen, LOCA could present a different picture of the future. Overall, we find that the peculiarities of specific decision-relevant metrics – such as this non-linear threshold-based chill hour metric – can lead to counterintuitive findings that question the validity of some generally accepted recommendations on climate model selection for impact and adaptation studies.

3.1.6 *Conclusion*

Decision-makers today have relatively easy web-based access to several different climate models and downscaled datasets. Yet, there is minimal guidance on the appropriate use of such models and projections for their specific adaptation context. In the few instances where recommendations for dataset choice and model selection are available, they are often based on model skill in broad physical climatic metrics, not in the specific decision-relevant metrics that underpin the adaptation action. While several of these studies acknowledge that their results are valid only for the metrics and time periods evaluated, very few papers have evaluated whether these broad physical climatic metrics indicate skill in specific decision-relevant metrics. To our knowledge, this is the first analysis (in California or elsewhere) to evaluate the implications of model choice for future projections of the decision-relevant metric of chill hours. Our assessment sheds light on some of the key differences between global versus local skill, and broad (physical climate) versus specific (decision-relevant agro climate) skill of climate models. The results also call into question some commonly accepted recommendations about dataset and model choice such as the prevalent use of LOCA datasets for adaptation studies in California, and the preference for the GCM multi-model mean sampling.

We acknowledge that skill assessment of every decision-relevant metric may not be a feasible option. Model assessments will most likely need to continue to focus on broader physical climate metrics, as they are vital for better understanding model performance on core climatic processes. Rather, we caution against blanket recommendations of datasets and models for all types of adaptation decisions without acknowledging the limitations of such broad-scale model evaluations. Since GCMs were not originally developed with decision-makers' needs in mind (Jones et al., 2016), it is important that they at least be evaluated through the lens of decision-relevant metrics. Such a "bottom-up" approach can help identify the relevant physical climatic metrics that most robustly represent decision relevant metrics. In this case, through our assessment we were able to identify monthly T_{min} and T_{av} and trend in winter season T_{min} and T_{av} as relevant physical climatic parameters for chill hours. We also find that the LOCA approach may need to be re-examined to identify the aspects of the downscaling that are likely causing the dataset to underestimate the negative slope in historical chill hours. This would shed light on LOCA's ability to predict chill hours as well as other non-linear decision-related metrics derived from climate model outputs.

Our research provides a better understanding of implications of model choice for future projections of the chill hours metric, which might be of interest to agricultural scientists, extension specialists, and adaptation experts who are interested in adaptation planning for perennial tree crops. Since many crucial adaptation decisions in agriculture, energy, water management, and other fields are made based on similar threshold-based metrics (such as growing degree days, heating or cooling degree days, and days over 100°F), further work on such bottom-up evaluations can provide critical insights on decision-relevant climate features, and implications of model selection for various decisions. In order to be truly effective, such bottom-up evaluations must be co-produced with scientists and sectoral decision-makers working jointly. Such collaborative evaluations can help provide stakeholders with the best available climate information for their specific adaptation contexts.

4. Co-production: A 'silver bullet' for improving the usability of climate science?

Chapters 2 and 3 highlight the importance of co-production for developing usable climate science that can assist adaptation decision-makers. However, as suggested in the introduction, not all co-production brings desirable outcomes, and the type and quality of scientist-stakeholder engagements often dictate the types of benefits that can be expected from co-production. In this last chapter of my dissertation I undertake an analysis of recent co-production projects (focusing on generating knowledge for climate change adaptation) to review the approaches and outcomes reported by these projects, and compare these to the many normative and theoretical aspirations of knowledge co-production. This comparison provides a reality-check on what to expect (and not expect) from co-production, and provides a way forward for co-production practice.

This chapter is currently being finalized for submission to an approved special issue in 'Current Opinion in Environmental Sustainability'. The paper has been included here with the permission of my co-authors Mr. James Arnott, Dr. Nicole Klenk, Dr. Katharine Mach, Dr. Richard Moss, Dr. K. Dana Sjostrom and Dr. Carina Wyborn. I led the design, data collection, coding, and analysis for this project with support from Mr. Arnott and Dr. Wyborn. The manuscript was developed in collaboration with all the co-authors.

4.1.1 *Introduction*

As climate change impacts are increasingly being experienced worldwide, there is a growing impetus to better connect scientific knowledge with the decisions and actions that can help societies adapt. Researchers and practitioners focused on climate change adaptation are now, in many instances, working interactively with each other to produce more decision-relevant or actionable knowledge. While these trends depart from the traditional norms of separation between science and society, they also reflect long-standing calls for more participatory and engaged research cultures. Thus, in a period of rapid climate change, new configurations to the science-society interface are emerging. Closer attention to this evolving landscape is essential to understand how science can better help society adapt to climate change and also to understand how changes in science could influence society in other, potentially more radical, ways.

In the realm of climate change adaptation science, co-production is becoming a widely accepted "best practice" for those who seek to (co-) generate actionable knowledge (Beier et al., 2017; Lemos and Morehouse, 2005) and promote more engaged models of research. A key driver here is the assumption that meaningful interactions between researchers and users of research will generate more accessible, relevant, and credible knowledge, thus increasing the likelihood of its use in practice. Some scholars and advocates also anticipate this will help reinvigorate or reconstitute the social contract between science and society. Yet there are few systematic assessments of what co-production effectively produces, for either its participants or other intended beneficiaries. Yet there are few systematic assessments of what outcomes co-production demonstrably achieves, for either its participants or intended beneficiaries. We seem to know enough about co-production to know that it can bear fruit, but not enough to know more specifically about the variety, quality, or abundance of its yield, and how this varies under different conditions. While myriad aspirations for co-production have emerged, ranging from generating enhanced and shared understandings to building adaptive capacity, and even facilitating transformative social and policy changes (Bremer and Meisch, 2017; Harvey et al., 2019), close observers are left to inquire whether these aims are achieved or, whether more ambition, or caution, is to be called for.

The purpose of this paper is to review the ideal outcomes of co-production (in the climate adaptation space) as theorized in the burgeoning literature on this topic alongside the recently reported outcomes from co-produced climate change adaptation projects. We start with a synthesis of the aspirational outcomes from contemporary theorization of co-production (Section 2). In Section 3, we conduct a thorough review of recent examples of on-the-ground co-production, reporting on their approaches and outcomes. In Section 4, we discuss the overlap and gaps between the theoretical outcomes and the actual outcomes reported in practice and why they occur, and finally in Section 5, we generate conclusions from our review and discuss what this means for the co-production practice moving forward.

4.1.2 *What co-production is expected to produce: Theorized outcomes*

Although co-production is now a widely used concept, different scholars and practitioners have, and continue to, interpret the term in divergent ways. Bremer and Meisch (2017) suggest that current co-production scholarship can be conceptualized in eight different dimensions each leading to different expectations in the type of outcomes or benefits from co-production. According to these eight lenses, outcomes can range from normative goals such as facilitating social learning about climate issues, developing useful climate information through interactions between science providers and users, and integrating non-scientists expertise in science, to the much loftier descriptive ambitions that suggest that co-production can change wider social, political and economic systems, and shape our representation of nature and society.

Two distinct perspectives exist regarding the theorized outcomes of co-production; ‘instrumental’ outcomes and ‘radical’ outcomes (Harvey et al., 2019; Klenk et al., 2017; Loeffler and Bovaird, 2016; Reed and Abernethy, 2018; Van der Hel, 2016). The instrumental outcomes focus on the benefits relating to production and dissemination of socially acceptable and decision-relevant knowledge and services. These can include benefits such as enhancing scientific accountability to society and including the perspectives of extra-scientific actors in science (Loeffler and Bovaird, 2016; Van der Hel, 2016). The more radical outcomes relate to transforming norms and institutional structures within science and society, such as fundamentally restructuring the ‘social’ contract for science and changing power structures and political systems (Gibbons, 1999). This latter perspective in the theoretical literature suggests that co-production, when done effectively, can open up decision-making spaces; reshape the science-public-policy interface; democratize science; broaden the scope and meaning of evidence in decision-making; and ultimately redistribute power and expertise among different groups within society (Gibbons, 2000; Gibbons et al., 1995; Latour, 1998).

In addition to the literature on the theoretical promise of co-production, there is a small but growing body of work on the empirical evidence for co-production outcomes within climate research based on a handful of case studies. Most of this literature finds that while co-production efforts have been reasonably successful in generating instrumental outcomes such as creation of relevant knowledge products, facilitating open dialogue across the science and practice communities, and building critical capacity to influence action (Harvey et al., 2019; Richards, 2018), these efforts have not necessarily led to more transformative outcomes such as social, governance or direct policy changes (Harvey et al., 2019; Richards, 2018; Wamsler, 2017). One study adds nuance by suggesting that in cases where co-production has been undertaken rigorously, it can achieve clear positive and in some cases radical outcomes. But when key elements (such as engagement over sustained periods, iterative reflect-act cycles, and challenging of institutional barriers) were neglected, suboptimal outcomes were seen (Van Epp and Garside, 2019). Some recent research in both co-production and adaptation has therefore focused attention on the political and institutional barriers to realizing broader aspirations of changes in policy and practice (Eisenhauer, 2016; Goldman et al., 2018; Klenk et al., 2017; Swart et al., 2014). These scholars have called for greater engagement with the politics of co-production (such as critically addressing power differentials between different actors), in ways that would recognize multiple ways of knowing and understanding climate change and lead to more radical changes in society.

4.1.3 *What co-production is actually producing: Actual Outcomes*

In order to provide a contemporary understanding of what is being co-produced in recent climate change adaptation projects, we consider examples around the world that were reported in the peer-reviewed literature published between 2016 and early 2019. We identified the papers through an exhaustive Scopus search, and short-listed them using screening criteria that is detailed in Appendix D. We identified 21 co-production projects, which were systematically reviewed to examine their intent, engagement approach, reported outputs & outcomes, and evaluation. For the sake of brevity, in this section we focus the actual outcomes, engagement approaches and evaluations undertaken in contemporary co-production practice.

4.1.3.1 Actual outcomes reported by co-production projects

Overall we found that co-production outcomes focus on one or more of the following: increasing utilization of knowledge, deepening understanding of climate issues, strengthening science-society communities, and either directly or indirectly catalyzing adaptation action (Figure 18). A majority of the projects we reviewed reported outcomes in terms of increasing utilization, deepening understanding and strengthening community. And only a few projects reported on an actual action that was undertaken as a result of the co-production work. Similar to the conclusions from Bremer and Meisch (2017), we also observed that these different perspectives often “converge, overlap, and influence” each other (p.13). Hence in our analysis we do not attempt a hard categorization of projects under each category, but rather cover the range of outcomes that these efforts encompass. The outcomes of the project manifested through a variety of outputs such as Publications; Communication & Outreach; Models & Decision Support Tools; Workshops & Educational Activities; Strategies, Plans, & Policies; Data & Concepts; and Direct Adaptation Interventions. Supplementary Material provides further details on these outputs.

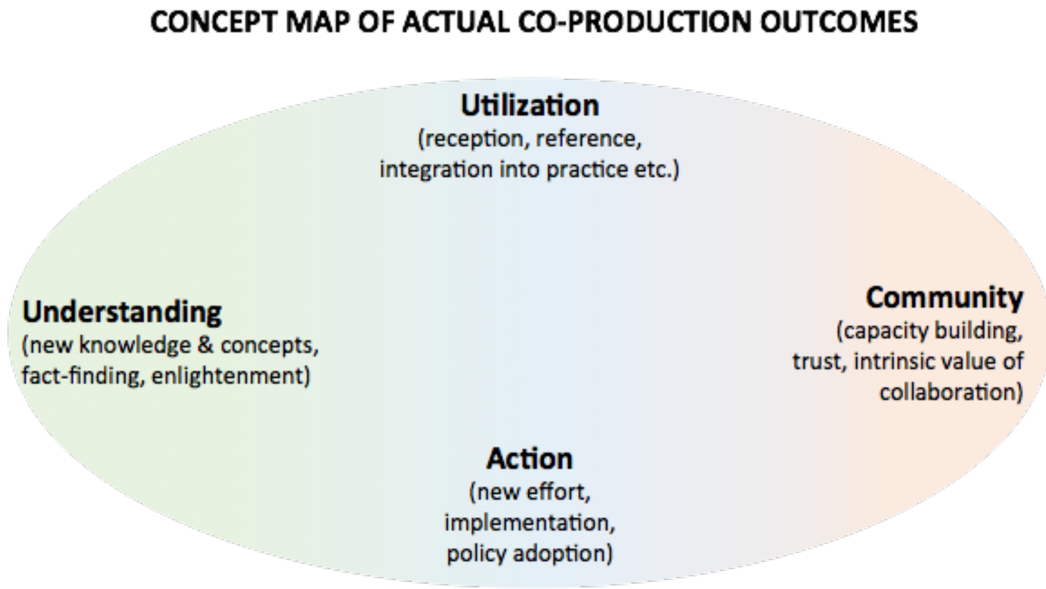

Figure 18: Concept map of co-production projects' reported outcomes. Note here that there are no categories of 'social change' or other radical outcomes that the theoretical literature expects, because few projects reported achieving these broader structural or transformative social and institutional changes.

Many project reported outcomes relating to a deepened understanding of climate change and adaptation by orienting co-production towards enabling a more holistic, integrated inclusion of non-academic and local knowledge, worldviews, experiences, and values (e.g., (Lavrillier and Gabyshev, 2018)). These projects often referenced literature on transdisciplinarity or the importance of non-academic forms of knowledge in adaptation. While in some instances it seemed that this deeper understanding would connect a particular instrumental outcome, such as by generating enhanced climate simulations or scenarios (Miller et al., 2017) or better understanding of local climate impacts, others were unbounded by utilitarian concerns. In fact, we found that many of the projects in our sample co-produce to stimulate reflection, learning and awareness amongst their participants, wherein the iterative and reflective process was the intended outcome, rather than just a means for the work (Aldunce et al., 2002; Borquez et al., 2017; Ruiu et al., 2017). For example: Rui et al. (2017) suggest that co-production can "*open space for people—including scientists and policy makers—to speak about their assumptions, values, and norms so that decisions become based less on the defense of autonomous interests and hidden meaning and more on appreciation of the interdependency of collective interests" (p.4)*. In instances like this, we may wonder whether this open space ultimately could lead to more radical possibilities despite the lack or inability to speak to them in the context of one journal article published soon after the completion of a project.

A majority of the projects also focused on strengthening community, both by forming bonds that enables science-practice collaboration or by fostering capacity in the community itself (Laursen et al., 2018). To support this approach, these projects referenced literature on Participatory Action Research (PAR) or the broader field of participation, where the engagement is valued more intrinsically than instrumentally. For example, in their application of co-production for an Australian NRM project, the authors (Wallis et al., 2017) candidly state that: *"Our approach was to form a collaborative partnership that favored discovery of information, rather than delivery." (p.43).* Key outcomes reported here were increased abilities to identify local impacts or solutions, and changes in the trust and capacity for collaboration amongst participants.

Increasing utilization of knowledge was either the latent or explicit outcome reported in several of the projects. These projects reported outcomes relating to the incorporation of new tools, models or knowledge in adaptation policies or plans. Many projects referenced foundational papers describing co-production as deliberate interactions between groups of actors with the aim of improving the use and usability of knowledge (e.g., (Dilling and Lemos, 2011; Lemos and Morehouse, 2005)). For example, (Jacobs et al., 2018), in describing their co-production effort with natural resources managers in New South Wales, explicitly align their co-production aim to the essential aspects they find in Lemos et al. (2012) including fit, flexibility, and resources:

> "*We believe that the process we employed in this study is an example of knowledge co-production because it: aimed specifically to gather, integrate and disseminate information relevant to regional planners and decision makers with the users of that information (demonstrating 'fit'); was co-designed with agency staff to ensure it was culturally appropriate (demonstrating flexibility); and, incorporated close consultation with senior [National Parks and Wildlife Service] decision-makers to ensure their support for and encouragement of participation by agency staff (securing resources)." (p. 207).*

Finally, we find that a few projects do explicitly seek to catalyze adaptation action. Here, we see the outcomes reported go beyond just incorporating the knowledge in policies and plans, and co-production is leveraged with the explicit aim for action, i.e., for example, to jointly implement adaptive farming practices in Malawi (Bezner Kerr et al., 2018) or to increase use of a planning tool and encourage decision-makers to take adaptive actions (Laudien et al., 2018). This suggests that some practitioners of co-production envision the potential for co-production as more than just a way to inform climate change adaptation with science – it can also be a means to stimulate adaptive action.

A key finding here was that very few projects reported achieving some of the more radical structural or transformative social and institutional changes that the theoretical conceptualization of co-production aspires. We discuss this in detail in the next section. A stark exception to this was the project reported by Bezner Kerr et al. (2018), which indicated broader social changes, such as increasing farmers' confidence in their observational skills and challenging dominant agricultural models. They state that:

> *"Co-production of knowledge using participatory methods, combined with agroecological approaches that used readily available resources, may have led*

farmers to trust their own experimentation and informal networks more in relation to climate-change adaptation", and "a participatory research model using agroecology can support experimentation with farming practices and increase knowledge sharing and flows, thereby challenging dominant agricultural models" p.249.

This project was also one of the few efforts that engaged with the broader political and power dynamics surrounding co-production, reporting a rare negative outcome of the process. The authors found that the farmers were blaming their own communities for ongoing deforestation, thus adopting dominant narratives attributing responsibility for environmental decline to smallholder farmers.

"Thus our co-produced knowledge, while spurring change in farming practice, also reinforced unequal power dynamics in unexpected ways, as critical scholars of climate-change adaptation have noted in other sites" p.249.

This example illustrates that, although rare in our systematic review, co-production efforts can appear to help bring about larger social changes but can also uncover (or even reinforce) some of these long-standing and often historically driven inequities related to disinvested or marginalized communities.

4.1.3.2 Engagement approaches used by co-production projects

In theory, the practice of co-production is not prescribed in advance, but instead is openly flexible to fit a particular context. One could therefore imagine a plethora of different engagement approaches to operationalize co-production. And while a growing set of papers address the underlying principles of co-production (Meadow et al., 2015) and attempt to formalize it in to "how-to guides" (Beier et al., 2017), we find in our review that the actual practice of co-producing adaptation knowledge is dominated by a surprisingly narrow set of engagement approaches to foster dialogue between researchers and practitioners. More than half (~12) describe conducting workshops as either the only or the primary mode of interaction, and most of the other projects describe some sort of organized meeting for group discussions and dialogue. But despite similarity in format, we observed that the duration and regularity of the engagements among these projects differed immensely, with some undertaking just one or a handful of meetings/workshops spanning a few days, and others lasting for several years. These engagements help achieve a variety of goals including the co-framing of research questions, training and education-oriented sessions for practitioners, and gathering feedback on results or beta versions of models and tools.

Perhaps surprisingly, given the linguistic logic embedded in the phrase, 'co-production of knowledge', it was less common to see researchers and practitioners jointly conducting scientific activities outside the context of discussions in workshops or similar settings. However, Lavrillier and Gabyshev (2018) and Bezner Kerr et al. (2018), are exceptions to the rule. These projects have co-produced knowledge in forms such as social network maps, model-based scenario planning tools, climatological observations in the field, and adaptation experiments on farms. While these cases show how some co-production techniques can serve to produce truly new understanding (in the sense of basic research), we note that a majority of projects that approached co-production in workshops or other settings focused on existing knowledge and trying to translate, package or interpret it a user-relevant manner.

Overall, our observations regarding the engagement approaches used for co-production raises an important question regarding the types and levels of engagement that can be expected in projects engaging in co-production. Is there a 'bare-minimum' level of engagement required for a project to be 'truly co-produced'? Or does the mode or level of engagement not matter, as long as projects' intents are being fulfilled? Or relatedly, does the mode or level of engagement depend on the scope of the co-production effort? And a further question also arises of whether the level of engagement is related to how co-production influences research across the landscape of so-called basic and applied pursuits of research.

4.1.3.3 EVALUATION

In terms of evaluations of co-production, more than half of the projects did not report undertaking any formal evaluations of the project process, outputs, or outcomes. This suggests that many of the outcomes reported, may not be backed by systematic assessments and hence remain speculative at this stage. When workshops were the primary mode of co-production, projects typically undertook user feedback surveys or workshop evaluations on the benefits of such an engagement, which vary in their ability to detect critical evaluations of the process. Some efforts provided reflective, anecdotal or observational evidence for some of the outcomes reported for example, and a couple of projects reported observing an increase in stakeholders' capacity and interest to understand climate change. Only a handful of the projects reported on undertaking more detailed evaluations of the co-production process and its outcomes. Most of these took a mixed methods approach where the evaluation included a combination of document analyses, structured observations, and interviews or focus groups. Two examples of evaluation stood out in our review. Kench et al. (2018), undertook a detailed document analysis of recorded meeting minutes, project outlines, and other internal project documents to trace shifts in the research objectives and processes, before and after co-production. Bezner Kerr et al. (2018) conducted quasi-experimental, case-control, pre-post longitudinal trials of different co-produced agro-ecological adaptation strategies. To evaluate the benefits, they undertook a baseline survey of the farmers before the project, followed by a series of post-project surveys to assess changes in agricultural practices, knowledge, and other social and environmental variables.

4.1.4 *COMPARING THEORETICAL CO-PRODUCTION OUTCOMES TO ACTUAL OUTCOMES*

Comparing the theoretical expectations of co-production to the actual outcomes reported in practice, we find that, while the contemporary practice achieves the instrumental outcomes of co-production, it falls well short in realizing the more radical outcomes that theory expects. This result corroborates and provides further project-based evidence to similar findings in some of the case study-based empirical literature on co-production (discussed in Section 4.1.2). To take this discussion further than just reporting this gap, we argue for a co-production research agenda that aims to generate more conversation, and potentially convergence, between co-production theory and practice, and between the intent and outcome of co-production (Figure 19). Using this research agenda, we analyzed whether the gap in actual co-production outcomes (mismatch in the red rectangle) exists because projects' intentions did not match their outcomes (green rectangle), or whether project's intentions do not encompass all of the theoretical intentions (purple rectangle). In other words, we examine whether the gap in actual outcomes is because co-production practice's intentions/aims are much more instrumental, or whether it is because the practice aims to achieve more radical outcomes but actually fall short of achieving them.

Through this review, we found that, for the most part, the contemporary practice of co-production for climate change adaptation tends to achieve the outcomes that they intend to i.e. there is no apparent discrepancy in the green box. However, we did find that very few projects explicitly aimed for the loftier more radical outcomes of co-production i.e. there is a potential imbalance in the purple box), which could explain why more instrumental outcomes of co-production are being reported as opposed to the broader ones. Therefore, although current co-production practice has been successful in creating more actionable knowledge it is yet to achieve more systemic changes in society.

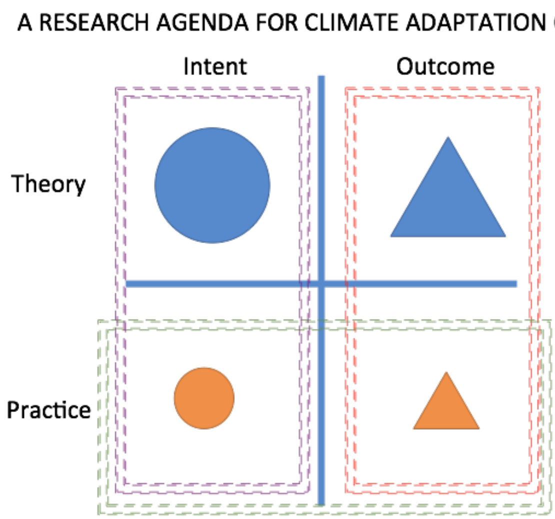

Figure 19: A research agenda for co-production of climate adaptation. Robust comparisons between theory, practice, intent, and outcome for co-production are needed. We review current literature to highlight insights from comparisons indicated by the green, purple and red rectangles. Specifically, we try to examine whether there is a match/mismatch: Between theoretical and actual outcomes (red box), Between projects' intents and outcomes they achieve (green box), Between theoretical intentions and intents in practice (violet box).

Finally, this review also pointed to five key reasons that can explain the limited outcomes we observe in contemporary co-production practice:

- **<u>Limited co-framing or co-designing of efforts</u>**: Although projects are largely implemented in a collaborative participatory manner, they often do not engage with stakeholders in co-framing or co-designing of the project, which is a critical aspect of co-production. So while the eventual knowledge is co-produced, the agency of the stakeholders is minimized if they do not have a say in the problem framing of the projects/research. This can limit the capacity of co-production to bring about more radical social or institutional changes. This was also exemplified in the fact that many projects conflated participatory research, transdisciplinary research or incorporating stakeholder inputs as co-production. While there are definitely elements of commonality, there are also some key differences between the approaches (such as those related to co-framing and co-designing research that are more specific to co-production) that may be important to highlight.

- **Successful but short-term engagements:** Another important aspect, was that several projects were executed through a one-off or just a handful of workshops or consultations, some of which may not amount to co-production by some definitions even though they self-describe as so. And while these one-off events were successful in bringing about changes in perspectives among participants, it is not clear how enduring these changes may be in the long-term. It is unclear whether a handful of workshops, even if apparently successful, are able to bring about long-term broader systemic changes.
- **Limited types of engagement approaches for a diversity of intentions:** It was also interesting to note that despite the diversity in intention or motivation of projects, a large majority of them undertook co-production through workshops or consultations. While there were definitely a few projects reporting some novel methodologies such as longitudinal analyses, collaborative fieldwork, using narrative analyses, or joint research through Memorandum of Understandings, the limited engagement methods could also contribute to the limited outcomes being reported.
- **Co-production used for value-add or translation of science, rather than for asking fundamental questions:** We also found that very few of the current co-production efforts reported on producing truly new understandings in the sense of fundamental or basic research. A close review of the projects suggested that this is perhaps closely linked with the length and type of engagements the projects undertook. All the projects that reported long-term and novel methods of engagements, also reported on producing new understandings (in the sense of fundamental research). These projects stood out in our review as exemplary use of co-production. On the other hand, most projects using shorter-term workshop like engagements, unsurprisingly, reported on outcomes relating to better translation or value-add to existing knowledge, which are more tangible outcomes to expect from such engagements. This shows that while there is a potential for co-production to integrate into more fundamental research and understandings, currently projects due to their limitations in engagements, are not adequately tapping into this potential.
- **Lack of evaluation of outcomes** makes it difficult to accurately ascertain the types of broader changes that may have been observed but not monitored or reported, or the validity of the outcomes reported.

While our review points to gaps in the intentions and aims of the co-production practise and highlights some specific areas for improvement, questions still remains as to whether the instrumental outcomes reported by co-production projects can be viewed as intermediary benefits on the path towards the more radical outcomes of co-production, and whether many such instrumental outcomes can combine to push the more transformative societal changes. Alternately, there is also a possibility that this instrumental focus takes away from, or even undermines the more radical possibilities of co-production. This begs another question of whether more should be expected of co-production practice, and whether its proponents and participants should seek to aim for more radical outcomes that are needed in order to create systems that can sustain the move towards a new social contract between science and society. A further question is also whether we can expect to see such radical outcomes at a project level (our unit of analysis), as opposed to a larger institutional analysis.

4.1.5 *Conclusions*

This paper brings together and compares the two streams of co-production, namely theory and action. We find that while the practice of knowledge co-production may be realizing improvements in knowledge utilization, among other beneficial outcomes, several issues arise that could catalyze important directions in future research. One is the apparent disconnect between the opportunity space of knowledge co-production, which may portend the possibility of more radical systemic changes of co-production, and the relatively incremental and instrumental ambition apparent in its current practice. Second, is to how the results of co-production in practice may be most appropriately evaluated against the intentions and resources invested in those efforts. Finally, a third issue is raised about the suitability of the project as a unit of analysis for understanding the outcomes of co-production.

We propose that to address these issues and unleash, or at least test, the full potential of co-production in support of climate change adaptation, a more transparent, conversant, and interactive research agenda and discourse is required. We call for more critical analysis and reporting of individual efforts to understand what they are intending and are not intending to do, how they are doing it, and what they are and are not achieving. Projects should also clarify the relationship between intent, approach and outcome; and substantiate their claims about outcomes. We find that there is a need to start acknowledging the lack of transformative intentions and approaches in co-production projects, and start conversations around this gap in order to push forward co-production in a more productive direction.

CONCLUSIONS

The four chapters of my dissertation illustrate that effective adaptation requires development of science that focuses on providing usable climate information to decision-makers. They also suggest that sustaining the production of actionable climate knowledge needs both scientists and decision-makers to transform the current science-society relationship. This calls for departure from the traditional norms of separation between science and society, and move towards long-standing calls for more participatory, engaged, and socially accountable research cultures. This new model of science is different from the existing 'ivory-tower' model, and is one where science is more accountable to society, is more strategic in addressing decision-makers' problems, incorporates plurality of viewpoints and expertise, and overall is more collaborative and porous.

In my opinion, the onus of the responsibility for creating this new science-society relationship is on us environmental scientists, particularly interdisciplinary scholars working on problem-driven research. Society requires scientists to work more deliberately towards decision-makers problems rather than serendipitously, as researchers often do. I conclude my dissertation with perspectives on what researchers and decision-makers respectively, can do better or differently to enable increased production of usable climate science and move towards a new 'social contract for science' that achieves more benefit to society.

<u>Way forward for researchers</u> (Figure 20)

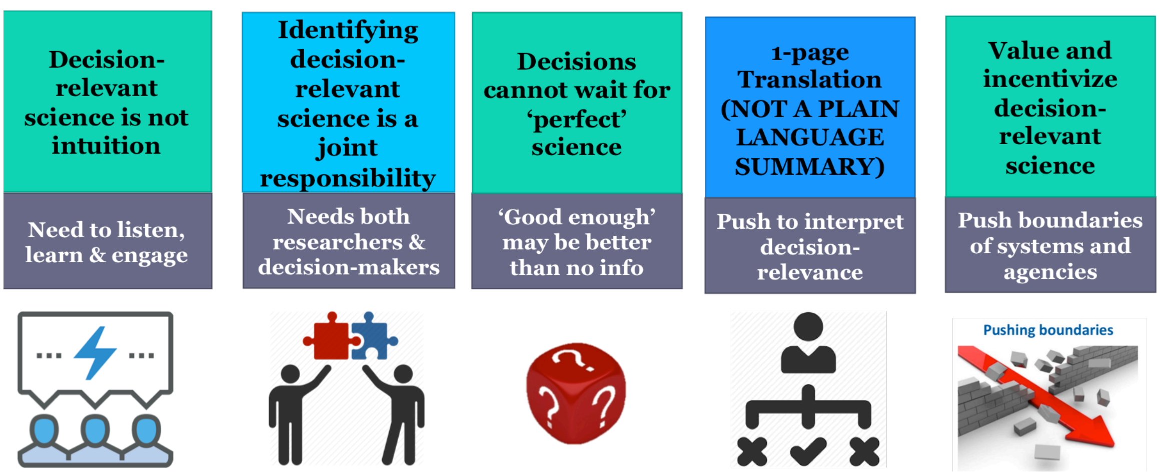

Figure 20: Five ways in which researchers can enable increased production of usable science

- **Decision-relevance is not intuition:** In order to develop truly actionable science, researchers cannot simply rely on their intuition or even just one-off meetings or conferences to understand what decision-makers need. Developing usable science necessarily requires that researchers engage with, patiently listen to, and recognize the expertise of decision-makers over a period of time. This includes engaging with these users before as well as during the course of their research to seek their opinion, and reflexively molding the science towards users' decision-contexts.

- **Identifying decision-relevant science is a joint responsibility:** Determining what decision-makers need in terms of science is a collective responsibility of both the decision-makers as well as the researchers. Researchers cannot expect that decision-makers will know in great detail all they need, as they may not know all that science has to offer to them in terms of both capabilities as well as the uncertainties in the science. Hence even identifying what decision-relevant science entails, is a collective and collaborative task.
- **Decisions cannot wait for 'perfect' science:** Many critical long-term management decisions such as how to design new storm water infrastructure or what types of tree crops to plant, are being undertaken now. And often these are being undertaken without any guidance from science, because researchers may feel like the science is not yet ready, and needs to be further improved. However adaptation is an urgent need, and decision-makers do not have the luxury of time to wait for an improved model or a better understanding of key processes. Decisions made today may last for 10, 20 or even a 100 years. This means that researchers may need to push themselves to provide tangible results to decision-makers even when the science may not be fully certain and precise. In some instances imperfect/uncertain/inaccurate may be better than no information at all. While care must be taken that researchers do not overstate or push the limits of their results too far that it impacts the credibility of their results, it is still important for researchers to push themselves to think about the decision-relevance of their outputs albeit imperfect. The threshold at which they can justifiably emphasize decision-relevance more than achieving precision is tricky, and must be arrived at on a case-to-case basis and in consultation with decision-makers.
- **Scientific papers need to be 'translated' for decision relevance:** Relatedly, researchers should translate their peer-reviewed scientific papers, for example through an accessibly written one-pager, to discuss why and how the results of the paper can be of relevance to decision-makers, and how they can potentially be used in adaptation decisions. Researchers can pick any decision-maker group and interpret results to their unique context. This 'translation' goes beyond just a plain language summary that simply presents the science. For example, it would require researchers go beyond just stating results such as temperatures are expected to rise by a certain number of degrees or that they developed a novel technique, and present ideas on how the temperature rise or the new method can be useful in specific decision-contexts.
- **Value and incentivize decision-relevant science:** Finally, researchers also need to push institutional systems to encourage and value such decision-relevant work. Current systems of scientific mandates and incentives do not adequately value decision-relevant science. Meaningful stakeholder engagement or co-production is inherently time consuming and resource intensive, as it requires several additional activities such as mediation, facilitation, extension, and communication. However, even in cutting-edge interdisciplinary departments, peer-reviewed publications continue to be the main metric of success, with the stakeholder engagement activities and non-journal based decision-relevant publications counting only as an add on. For decision-relevant science, journals or fellow scientists do not always represent the right set of 'peers', and hence different metrics of success (such as quality and level of stakeholder involvement in the science, user-relevant reports or communication

material) may be more appropriate. Unless such work is valued equally in an institutional context, researchers will not be able to do justice to the time and effort needed to do such work.

<u>Way forward for decision-makers</u> (Figure 21)

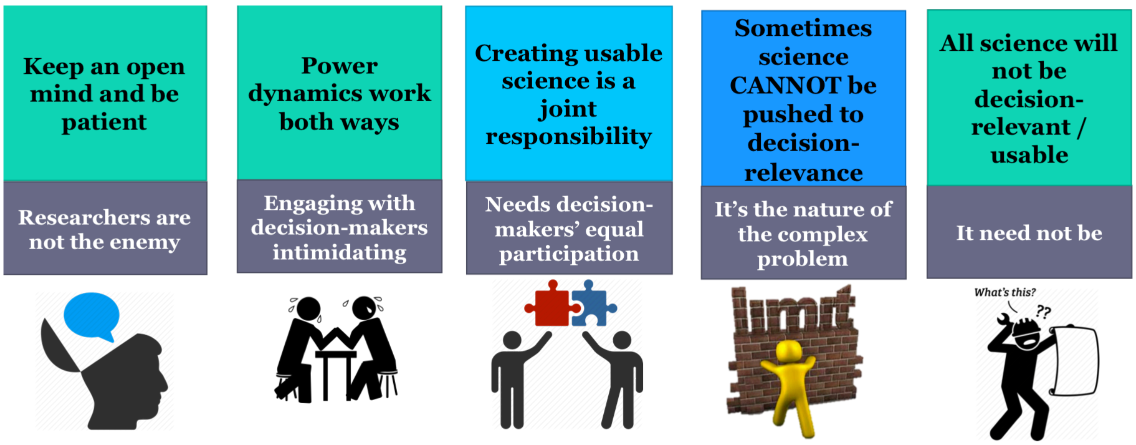

Figure 21: Five ways in which decision-makers can enable increased production of usable science

- **Keep an open mind and be patient with researchers**. Although decision-makers have an urgent need for actionable science, scientific research in this complex problem space can often take longer. Decision-makers need to be patient, because there may be a lot of well-meaning researchers who are operating within institutional systems and scientific cultures that are not very conducive to decision-relevant work.
- **Power dynamics can work both ways:** Engaging with decision-makers can be intimidating to scientists too, as not everyone is skilled at such interactions. Often times, power dynamics can work in unexpected ways, for example sometimes scientists are very intimidated to interact with a farmer or a resource manager. Hence, decision-makers need to be aware and cognizant of these 'reverse' power dynamics.
- **Creating usable science requires decision-makers' equal participation:** Decision-makers cannot expect researchers to come up with decision-relevant science by themselves. It needs equal involvement of both parties, and both types of experts to work together for the science to be truly actionable.
- **Sometimes science cannot be pushed to decision-relevance:** Climate change is complex, and sometimes decision-makers may need to acknowledge that the nature of the problem is such that researchers may not have the all answers to their questions.
- **All science will not be decision-relevant or usable, and it need not be**: As important as it is to engage in decision-relevant science, researchers always need room to also pursue the more 'non-engaged' forms of science which are more serendipitous or discovery-driven. These are equally important as they push the boundaries of how we know and understand the world.

<u>Overall suggestions</u>

- **Training on collaborative research processes:** Overall, such a shift towards a new science-society relationship requires training both scientists and decision-makers on collaborative learning and research processes. In order to effectively work together, the two groups will need to spend time in educating and learning about each other, and in developing a shared language and frame of reference (Lele and Norgaard, 2005).

- **Develop, train, value and incentivize boundary agencies:** Bringing scientists and decision-makers together also needs effective agencies or individuals who manage the boundaries of science-and-policy or science-and-action. These boundary management agencies or individuals are critical actors in mediating and facilitating these crucial but difficult collaborations across epistemic communities. They are responsible for creating settings where scientists and stakeholders collaborate yet maintain their specific accountabilities and identities (Kirchhoff et al., 2015a). Recent evidence has shown that boundary agencies/spanners such as the Regional Integrated Science and Applications Program (RISA), The Lenfest Ocean Program, and the California Ocean Science Trust, have been successful in bridging and brokering scientist-decision maker interactions and in promoting the development of usable science for decision-making (Bednarek et al., 2018; Kirchhoff et al., 2015b). Such institutions and individuals need to be developed, trained, valued, and incentivized in order to sustain these new science-society relationships.

REFERENCES

Adger, W.N., Agrawala, S., Mirza, M.M.Q., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., Takahashi, K., 2007. Assessment of adaptation practices, options, constraints and capacity, in: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Adger, W.N., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. Glob. Environ. Chang. 15, 77–86. https://doi.org/10.1016/j.gloenvcha.2004.12.005

Aldunce, P., Bórquez, R., Adler, C., Blanco, G., Garreaud, R., 2002. Unpacking Resilience for Adaptation : Incorporating Practitioners ' Experiences through a Transdisciplinary Approach to the Case of Drought in Chile 1–21. https://doi.org/10.3390/su8090905

Ames, G.K., Dufour, R., 2014. Climate Change and Perennial Fruit and Nut Production : Investing in Resilience in Uncertain Times. Natl. Cent. Appropr. Technol. Agric. IP476, 12.

Arbuckle, J.G., Haigh, T., Hobbs, J., Knoot, T., 2013. Climate change beliefs , concerns , and attitudes toward adaptation and mitigation among farmers in the Midwestern United States. Drought Mitig. Cent. Fac. Publ. 11.

Ayers, J., Dodman, D., 2010. Climate change adaptation and development I: the state of the debate. Prog. Dev. Stud. 10, 161–168. https://doi.org/10.1177/146499340901000205

Baldocchi, D., Wong, S., 2007. Accumulated winter chill is decreasing in the fruit growing regions of California. Clim. Change 87, 153–166. https://doi.org/10.1007/s10584-007-9367-8

Baron, J.S., Griffith, B., Joyce, L.A., Kareiva, P., Keller, B.D., Palmer, M.A., Peterson, C.H., Scott, J.M., 2008. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Synthesis and Assessment Product. Washington, D.C.

Barsugli, J.J., Guentchev, G., Horton, R.M., Wood, A., Mearns, L.O., Liang, X.-Z., Winkler, J. a., Dixon, K., Hayhoe, K., Rood, R.B., Goddard, L., Ray, A., Buja, L., Ammann, C., 2013. The practitioner's dilemma: How to assess the credibility of downscaled climate projections. Eos, Trans. Am. Geophys. Union 94, 424–425. https://doi.org/10.1002/2013EO460005

Bartels, W.L., Furman, C.A., Diehl, D.C., Royce, F.S., Dourte, D.R., Ortiz, B. V., Zierden, D.F., Irani, T.A., Fraisse, C.W., Jones, J.W., 2013. Warming up to climate change: A participatory approach to engaging with agricultural stakeholders in the

Southeast US. Reg. Environ. Chang. 13, 45–55. https://doi.org/10.1007/s10113-012-0371-9

Bednarek, A.T., Shouse, B., Hudson, C.G., Goldburg, R., 2016. Science-policy intermediaries from a practitioner's perspective: The Lenfest Ocean Program experience. Sci. Public Policy 43, 291–300. https://doi.org/10.1093/scipol/scv008

Bednarek, A.T., Wyborn, C., Cvitanovic, C., Meyer, R., Colvin, R.M., Addison, P.F.E., Close, S.L., Curran, K., Farooque, M., Goldman, E., Hart, D., Mannix, H., McGreavy, B., Parris, A., Posner, S., Robinson, C., Ryan, M., Leith, P., 2018. Boundary spanning at the science–policy interface: the practitioners' perspectives. Sustain. Sci. 13, 1175–1183. https://doi.org/10.1007/s11625-018-0550-9

Beier, P., Hansen, L.J., Helbrecht, L., Behar, D., 2017. A How-to Guide for Coproduction of Actionable Science. Conserv. Lett. 10, 288–296. https://doi.org/10.1111/conl.12300

Berrang-Ford, L., Ford, J.D., Paterson, J., 2011. Are we adapting to climate change? Glob. Environ. Chang. 21, 25–33. https://doi.org/10.1016/j.gloenvcha.2010.09.012

Bezner Kerr, R., Nyantakyi-Frimpong, H., Dakishoni, L., Lupafya, E., Shumba, L., Luginaah, I., Snapp, S.S., 2018. Knowledge politics in participatory climate change adaptation research on agroecology in Malawi. Renew. Agric. Food Syst. 33, 238–251. https://doi.org/10.1017/S1742170518000017

Biesbroek, G.R., Klostermann, J.E.M., Termeer, C.J. a M., Kabat, P., 2013. On the nature of barriers to climate change adaptation. Reg. Environ. Chang. 13, 1119–1129. https://doi.org/10.1007/s10113-013-0421-y

Borquez, R., Aldunce, P., Adler, C., 2017. Resilience to climate change: from theory to practice through co-production of knowledge in Chile. Sustain. Sci. 12, 163–176. https://doi.org/10.1007/s11625-016-0400-6

Brekke, L.D., Dettinger, M.D., Maurer, E.P., Anderson, M., 2008. Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments. Clim. Change 89, 371–394. https://doi.org/10.1007/s10584-007-9388-3

Bremer, S., Meisch, S., 2017. Co-production in climate change research: reviewing different perspectives. Wiley Interdiscip. Rev. Clim. Chang. 8. https://doi.org/10.1002/wcc.482

Briley, L., Brown, D., Kalafatis, S.E., 2015. Overcoming barriers during the co-production of climate information for decision-making. Clim. Risk Manag. 9, 41–49. https://doi.org/10.1016/j.crm.2015.04.004

Brink, E., Aalders, T., Ádám, D., Feller, R., Henselek, Y., Hoffmann, A., Ibe, K., Matthey-Doret, A., Meyer, M., Negrut, N.L., Rau, A.L., Riewerts, B., von Schuckmann, L., Törnros, S., von Wehrden, H., Abson, D.J., Wamsler, C., 2016.

Cascades of green: A review of ecosystem-based adaptation in urban areas. Glob. Environ. Chang. 36, 111–123. https://doi.org/10.1016/j.gloenvcha.2015.11.003

Cal-Adapt, 2017. Underlying Data and Model Selection in Cal- Adapt 2.0 [WWW Document]. URL https://cal-adapt.org/blog/2017/underlying-data-and-model-selection-in-cal-adapt-2-0/ (accessed 2.7.18).

Carlson, K., McCormick, S., 2015. American adaptation: Social factors affecting new developments to address climate change. Glob. Environ. Chang. 35, 360–367. https://doi.org/10.1016/j.gloenvcha.2015.09.015

Cash, D.W., Borck, J.C., 2006. Countering the Loading-Dock Approach to Oscillation (ENSO) Forecasting Systems 465–494.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. U. S. A. 100, 8086–8091. https://doi.org/10.1073/pnas.1231332100

CATRWG, 2017. Projected Climate Scenarios Selected to Represent a Range of Possible Futures in California Description. Sacramento, CA.

CCTAG, 2015. Perspectives and Guidance for Climate Change Analysis. Sacramento, CA.

CDFA, 2016. California Agricultural Statistics Review 2015-2016. Sacramento, CA.

Chong, J., 2014. Ecosystem-based approaches to climate change adaptation: progress and challenges. Int. Environ. Agreements Polit. Law Econ. 14, 391–405. https://doi.org/10.1007/s10784-014-9242-9

Clar, C., Prutsch, A., Steurer, R., 2013. Barriers and guidelines for public policies on climate change adaptation: A missed opportunity of scientific knowledge-brokerage. Nat. Resour. Forum 37, 1–18. https://doi.org/10.1111/1477-8947.12013

County of Fresno, 2015. 2015 Fresno County Annual Crop & LIvestock Report. Fresno, CA.

Crane, T.A., Roncoli, C., Paz, J., Breuer, N., Broad, K., Ingram, K.T., Hoogenboom, G., 2010. Forecast Skill and Farmers' Skills: Seasonal Climate Forecasts and Agricultural Risk Management in the Southeastern United States. Weather. Clim. Soc. 2, 44–59. https://doi.org/10.1175/2009WCAS1006.1

Daniels, A.E., Morrison, J.F., Joyce, L.A., Croosktion, N.L., Chen, S.C., McNulty, S.G., 2012. Climate projections FAQ, Gen. Tech. Rep. RMRS-GTR-277WWW. Fort Collins, CO.

Darbyshire, R., Webb, L., Goodwin, I., Barlow, S., 2011. Winter chilling trends for deciduous fruit trees in Australia. Agric. For. Meteorol. 151, 1074–1085. https://doi.org/10.1016/j.agrformet.2011.03.010

Dessai, S., Hulme, M., Lempert, R., Pielke Jr, R., 2009. Climate prediction: a limit to adaptation, in: Adger, W.N., Lorenzoni, I., Karen, L.O. (Eds.), Adapting to Climate Change: Thresholds, Values, Governance. Cambridge University Press, pp. 64–78. https://doi.org/http://dx.doi.org/10.1017/CBO9780511596667.006

Dessai, S., Lu, X., Risbey, J.S., 2005. On the role of climate scenarios for adaptation planning. Glob. Environ. Chang. 15, 87–97. https://doi.org/10.1016/j.gloenvcha.2004.12.004

Dilling, L., Lackstrom, K., Haywood, B., Dow, K., Lemos, M.C., Berggren, J., Kalafatis, S., 2014. What Stakeholder Needs Tell Us about Enabling Adaptive Capacity: The Intersection of Context and Information Provision across Regions in the United States. Weather. Clim. Soc. 7, 5–17. https://doi.org/10.1175/WCAS-D-14-00001.1

Dilling, L., Lemos, M.C., 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. Glob. Environ. Chang. 21, 680–689. https://doi.org/10.1016/j.gloenvcha.2010.11.006

Doll, D., 2013. Winter Chill Reduction from Climate Change. Almond Dr. - Univ. Calif. Agric. Nat. Resour.

Doll, D., Beede, B., 2016. Winter Chill Update : December 2016. Almond Dr. - Univ. Calif. Agric. Nat. Resour.

Doll, J.E., Petersen, B., Bode, C., 2017. Skeptical but Adapting: What Midwestern Farmers Say about Climate Change. Weather. Clim. Soc. 9, 739–751. https://doi.org/10.1175/wcas-d-16-0110.1

Doswald, N., Munroe, R., Roe, D., Giuliani, A., Castelli, I., Stephens, J., Möller, I., Spencer, T., Vira, B., Reid, H., 2014. Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. Clim. Dev. 6, 1–17. https://doi.org/10.1080/17565529.2013.867247

Doswald, N., Osti, M., 2011. Ecosystem-based approaches to adaptation and mitigation- Good practice examples and lessons learned in Europe, Research Report. Bundesamt für Naturschutz (BfN) Federal Agency for Nature Conservation, Bonn, Germany.

Dupuis, J., Biesbroek, R., 2013. Comparing apples and oranges: The dependent variable problem in comparing and evaluating climate change adaptation policies. Glob. Environ. Chang. 23, 1476–1487. https://doi.org/10.1016/j.gloenvcha.2013.07.022

Eisenhauer, D.C., 2016. Pathways to Climate Change Adaptation: Making Climate Change Action Political. Geogr. Compass 10, 207–221. https://doi.org/10.1111/gec3.12263

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., Rummukainen, M., 2013. Evaluation of Climate Models. Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep.

Intergov. Panel Clim. Chang. 741–866. https://doi.org/10.1017/CBO9781107415324

Ford, J., Lea, B.F., Alex, L., Jody, B.M. and H., 2013. How to track climate change adaptation: A typology of approaches for national-level application. Ecol. Soc. 18. https://doi.org/10.5751/ES-05732-180340

Fortmann, L., 2008. Participatory research in conservation and rural livelihoods : doing science together. Chichester: Wiley-Blackwell.

Gibbons, M., 2000. Mode 2 society and the emergence of context-sensitive science. Sci. Public Policy 27, 159–163. https://doi.org/10.3152/147154300781782011

Gibbons, M., 1999. Science's new social contract with society. Nature 402, 81–84. https://doi.org/10.1038/35011576

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1995. The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. Contemp. Sociol. 24, 751. https://doi.org/10.2307/2076669

Girvetz, E.H., Maurer, E., Duffy, P., Ruesch, A., Thrasher, B., Zganjar, C., 2013. Making Climate Data Relevant to Decision Making: The important details of Spatial and Temporal Downscaling 43.

Goldman, M.J., Turner, M.D., Daly, M., 2018. A critical political ecology of human dimensions of climate change: Epistemology, ontology, and ethics. Wiley Interdiscip. Rev. Clim. Chang. 1–15. https://doi.org/10.1002/wcc.526

Grantham, T., Kearns, F., Kocher, S., Roche, L., Pathak, T., 2017. Building climate change resilience in California through UC Cooperative Extension. Calif. Agric. 71, 197–200.

Hackenbruch, J., Kunz-Plapp, T., Müller, S., Schipper, J., 2017. Tailoring Climate Parameters to Information Needs for Local Adaptation to Climate Change. Climate 5, 25. https://doi.org/10.3390/cli5020025

Hansen, J.W., 2002. Realizing the potential benefits of climate prediction to agriculture: Issues, approaches, challenges. Agric. Syst. 74, 309–330. https://doi.org/10.1016/S0308-521X(02)00043-4

Harvey, B., Cochrane, L., Van Epp, M., 2019. Charting co-production pathways in climate and development programming and practice. Environ. Policy Gov. 1–11. https://doi.org/10.1002/eet.1834

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M., Wolfe, D., 2011. Climate impacts on agriculture: Implications for crop production. Agron. J. 103, 351–370. https://doi.org/10.2134/agronj2010.0303

Hawkins, E., Osborne, T.M., Ho, C.K., Challinor, A.J., 2013. Calibration and bias correction of climate projections for crop modelling: An idealised case study over Europe. Agric. For. Meteorol. 170, 19–31.

https://doi.org/10.1016/j.agrformet.2012.04.007

Hawkins, E., Sutton, R., 2009. The potential to narrow uncertainty in regional climate predictions. Bull. Am. Meteorol. Soc. 90, 1095–1107. https://doi.org/10.1175/2009BAMS2607.1

Hegger, D., Lamers, M., Van Zeijl-Rozema, A., Dieperink, C., 2012. Conceptualising joint knowledge production in regional climate change adaptation projects: Success conditions and levers for action. Environ. Sci. Policy 18, 52–65. https://doi.org/10.1016/j.envsci.2012.01.002

Hinckle, P., 2015. Warm winters could mean less fruit harvested in California. The Fruitguys.

Howden, S.M., Soussana, J.-F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. Proc. Natl. Acad. Sci. 104, 19691–19696. https://doi.org/10.1073/pnas.0701890104

Hudlicka, E., 1996. Requirements elicitation with indirect knowledge elicitation techniques: comparison of three methods, in: Proceedings of the Second International Conference on Requirements Engineering. pp. 4–11. https://doi.org/10.1109/ICRE.1996.491424

IPCC, 2014. Summary for Policymakers, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 1–32.

IPCC, 2013a. Summary for Policymakers, in: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30. https://doi.org/10.1017/CBO9781107415324.004

IPCC, 2013b. Annex III: Glossary, in: Stocker, T.., Qin, D., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1447–1466.

Jacobs, B., Boronyak, L., Mitchell, P., Vandenberg, M., Batten, B., 2018. Towards a climate change adaptation strategy for national parks: Adaptive management pathways under dynamic risk. Environ. Sci. Policy 89, 206–215.

https://doi.org/10.1016/j.envsci.2018.08.001

Jones, A., Calvin, K., Lamarque, J.-F., 2016. Climate Modeling with Decision Makers in Mind. Eos (Washington. DC). 97, 2–5. https://doi.org/10.1029/2016EO051111

Jones, H.P., Hole, D.G., Zavaleta, E.S., 2012. Harnessing nature to help people adapt to climate change. Nat. Clim. Chang. 2, 504–509. https://doi.org/10.1038/nclimate1463

Jones, J.W., Hansen, J.W., Royce, F.S., Messina, C.D., 2000. Potential benefits of climate forecasting to agriculture. Agric. Ecosyst. Environ. 82, 169–184. https://doi.org/10.1016/S0167-8809(00)00225-5

Kerr, A., Dialesandro, J., Steenwerth, K., Lopez-Brody, N., Elias, E., 2018. Vulnerability of California specialty crops to projected mid-century temperature changes. Clim. Change 148, 419–436. https://doi.org/10.1007/s10584-017-2011-3

Kettle, N.P., Dow, K., 2016. The Role of Perceived Risk, Uncertainty, and Trust on Coastal Climate Change Adaptation Planning. Environ. Behav. 48, 579–606. https://doi.org/10.1177/0013916514551049

Khan, M.R., Roberts, J.T., 2013. Adaptation and international climate policy. Wiley Interdiscip. Rev. Clim. Chang. 4, 171–189. https://doi.org/10.1002/wcc.212

Kirchhoff, C.J., 2013. Understanding and enhancing climate information use in water management. Clim. Change 119, 495–509. https://doi.org/10.1007/s10584-013-0703-x

Kirchhoff, C.J., Carmen Lemos, M., Dessai, S., 2013a. Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science. Annu. Rev. Environ. Resour. 38, 393–414. https://doi.org/10.1146/annurev-environ-022112-112828

Kirchhoff, C.J., Esselman, R., Brown, D., 2015a. Boundary organizations to boundary chains: Prospects for advancing climate science application. Clim. Risk Manag. 9, 20–29. https://doi.org/10.1016/j.crm.2015.04.001

Kirchhoff, C.J., Lemos, M.C., Engle, N.L., 2013b. What influences climate information use in water management? The role of boundary organizations and governance regimes in Brazil and the U.S. Environ. Sci. Policy 26, 6–18. https://doi.org/10.1016/j.envsci.2012.07.001

Kirchhoff, C.J., Lemos, M.C., Kalafatis, S., 2015b. Narrowing the gap between climate science and adaptation action: The role of boundary chains. Clim. Risk Manag. 9, 1–5. https://doi.org/10.1016/j.crm.2015.06.002

Klein R.J.T., Midgley, G.F., Preston, B.L., Alam, M., Berkhout, F.G.H., Dow, K., Shaw, M.R., 2014. 16. Adaptation Opportunities, Constraints, and Limits. Assess. Rep. 5-Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Part A Glob. Sect. Asp. 899–943.

Klenk, N., Fiume, A., Meehan, K., Gibbes, C., 2017. Local knowledge in climate adaptation research: moving knowledge frameworks from extraction to co-production. Wiley Interdiscip. Rev. Clim. Chang. 8. https://doi.org/10.1002/wcc.475

Klenk, N.L., Meehan, K., Pinel, S.L., Mendez, F., Lima, P.T., Kammen, D.M., 2015. Stakeholders in climate science : Beyond lip service ? Science (80-.). 743, 743–744. https://doi.org/10.1126/science.aab1495

Koch, E.W., Barbier, E.B., Silliman, B.R., Reed, D.J., Perillo, G.M.E., Hacker, S.D., Granek, E.F., Primavera, J.H., Muthiga, N., Polasky, S., Halpern, B.S., Kennedy, C.J., Kappel, C. V., Wolanski, E., 2009. Non-linearity in ecosystem services: Temporal and spatial variability in coastal protection. Front. Ecol. Environ. 7, 29–37. https://doi.org/10.1890/080126

Kundzewicz, Z.W., Stakhiv, E.Z., 2010. Are climate models “ready for prime time” in water resources management applications, or is more research needed? Hydrol. Sci. J. 55, 1085–1089. https://doi.org/10.1080/02626667.2010.513211

Latour, B., 1998. Essays on science and society: From the World of Science to the World of Research? Science (80-.). 280, 208–209. https://doi.org/10.1126/science.280.5361.208

Laudien, R., Boon, E., Goosen, H., van Nieuwaal, K., 2018. The Dutch adaptation web portal: seven lessons learnt from a co-production point of view. Clim. Change 1–13. https://doi.org/10.1007/s10584-018-2179-1

Laursen, S., Puniwai, N., Genz, A.S., Nash, S.A.B., Canale, L.K., Ziegler-Chong, S., 2018. Collaboration Across Worldviews: Managers and Scientists on Hawai‘i Island Utilize Knowledge Coproduction to Facilitate Climate Change Adaptation. Environ. Manage. 62, 619–630. https://doi.org/10.1007/s00267-018-1069-7

Lavrillier, A., Gabyshev, S., 2018. An emic science of climate. Reindeer Evenki environmental knowledge and the notion of an “extreme process.” Études Mongoles Et Sibériennes, Centrasiatiques Et Tibétaines. https://doi.org/10.4000/emscat.3280

Lele, S., Norgaard, R.B., 2005. Practicing interdisciplinarity. Bioscience 55, 967–975.

Lemos, M.C., 2015. Usable climate knowledge for adaptive and co-managed water governance. Curr. Opin. Environ. Sustain. 12, 48–52. https://doi.org/10.1016/j.cosust.2014.09.005

Lemos, M.C., Arnott, J.C., Ardoin, N.M., Baja, K., Bednarek, A.T., Dewulf, A., Fieseler, C., Goodrich, K.A., Jagannathan, K., Klenk, N., Mach, K.J., Meadow, A.M., Meyer, R., Moss, R., Nichols, L., Sjostrom, K.D., Stults, M., Turnhout, E., Vaughan, C., Wong-Parodi, G., Wyborn, C., 2018. To co-produce or not to co-produce. Nat. Sustain. 1, 722–724. https://doi.org/10.1038/s41893-018-0191-0

Lemos, M.C., Kirchhoff, C.J., Ramprasad, V., 2012. Narrowing the climate information usability gap. Nat. Clim. Chang. 2, 789–794. https://doi.org/10.1038/nclimate1614

Lemos, M.C., Lo, Y.J., Kirchhoff, C., Haigh, T., 2014. Crop advisors as climate information brokers: Building the capacity of us farmers to adapt to climate change. Clim. Risk Manag. 4, 32–42. https://doi.org/10.1016/j.crm.2014.08.001

Lemos, M.C., Morehouse, B.J., 2005. The co-production of science and policy in integrated climate assessments. Glob. Environ. Chang. 15, 57–68. https://doi.org/10.1016/j.gloenvcha.2004.09.004

Lemos, M.C., Rood, R.B., 2010. Climate projections and their impact on policy and practice. Wiley Interdiscip. Rev. Clim. Chang. 1, 670–682. https://doi.org/10.1002/wcc.71

Lempert, R.J., Groves, D.G., 2010. Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. Technol. Forecast. Soc. Change 77, 960–974. https://doi.org/10.1016/j.techfore.2010.04.007

Lempert, R.J., Popper, S.W., Groves, D.G., Kalra, N., Fischbach, J.R., Bankes, S.C., Bryant, B.P., Collins, M.T., Keller, K., Hackbarth, A., Dixon, L., LaTourrette, T., Reville, R.T., Hall, J.W., Mijere, C., McInerney., D.J., 2013. Making Good Decisions Without Predictions: Robust Decision Making for Planning Under Deep Uncertainty. Santa Monica, CA.

Lobell, D.B., Field, C.B., 2011. California perennial crops in a changing climate. Clim. Change 109, 317–333. https://doi.org/10.1007/s10584-011-0303-6

Lobell, D.B., Field, C.B., Cahill, K.N., Bonfils, C., 2006. Impacts of future climate change on California perennial crop yields: Model projections with climate and crop uncertainties. Agric. For. Meteorol. 141, 208–218. https://doi.org/10.1016/j.agrformet.2006.10.006

Loeffler, E., Bovaird, T., 2016. User and Community Co-Production of Public Services: What Does the Evidence Tell Us? Int. J. Public Adm. 39, 1006–1019. https://doi.org/10.1080/01900692.2016.1250559

Lövbrand, E., 2011. Co-producing European climate science and policy: a cautionary note on the making of useful knowledge. Sci. Public Policy 38(3), 225–236. https://doi.org/10.3152/030234211x12924093660516

Lu, X., 2009. Applying climate information for adaptation decision-making: A guidance and resource document, National Communications Support Programme. New York,USA.

Luedeling, E., 2012. Climate change impacts on winter chill for temperate fruit and nut production : A review. Sci. Hortic. (Amsterdam). 144, 218–229. https://doi.org/10.1016/j.scienta.2012.07.011

Luedeling, E., Girvetz, E.H., Semenov, M. a, Brown, P.H., 2011. Climate change affects winter chill for temperate fruit and nut trees. PLoS One 6, e20155. https://doi.org/10.1371/journal.pone.0020155

Luedeling, E., Zhang, M., Girvetz, E.H., 2009a. Climatic changes lead to declining winter chill for fruit and nut trees in California during 1950-2099. PLoS One 4, 1–9. https://doi.org/10.1371/journal.pone.0006166

Luedeling, E., Zhang, M., Luedeling, V., Girvetz, E.H., 2009b. Sensitivity of winter chill models for fruit and nut trees to climatic changes expected in California's Central Valley. Agric. Ecosyst. Environ. 133, 23–31. https://doi.org/10.1016/j.agee.2009.04.016

Maraun, D., Widmann, M., Gutiérrez, J.M., Kotlarski, S., Chandler, R.E., Hertig, E., Wibig, J., Huth, R., Wilcke, R.A.I., 2015. VALUE: A framework to validate downscaling approaches for climate change studies. Earth's Futur. 3, 1–14.

Mase, A.S., Prokopy, L.S., 2013. Unrealized Potential: A Review of Perceptions and Use of Weather and Climate Information in Agricultural Decision Making. Weather. Clim. Soc. 6, 47–61. https://doi.org/10.1175/WCAS-D-12-00062.1

Maurer, E.P., Brekke, L., Pruitt, T., Thrasher, B., Long, J., Duffy, P., Dettinger, M., Cayan, D., Arnold, J., 2014. An enhanced archive facilitating climate impacts and adaptation analysis. Bull. Am. Meteorol. Soc. 95, 1011–1019. https://doi.org/10.1175/BAMS-D-13-00126.1

Mcgray, H., Hammill, A., Bradley, R., Schipper, L.E., Parry, J.-E., 2007. Weathering the Storm - Options for Framing Adaptation, WRI Report. World Resources Institute. Washington, DC.

McNie, E.C., 2008. Co-producing useful climate science for policy: Lessons from the RISA program. ProQuest.

McNie, E.C., 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environ. Sci. Policy 10, 17–38. https://doi.org/10.1016/j.envsci.2006.10.004

Mcnie, E.C., Parris, A., Sarewitz, D., 2013. A Typology for Assessing the Role of Users in Scientific Research : Discussion Paper 1–15.

McSweeney, C.F., Jones, R.G., Booth, B.B.B., 2012. Selecting Ensemble Members to Provide Regional Climate Change Information. J. Clim. 25, 7100–7121. https://doi.org/10.1175/JCLI-D-11-00526.1

McSweeney, C.F., Jones, R.G., Lee, R.W., Rowell, D.P., 2014. Selecting CMIP5 GCMs for downscaling over multiple regions. Clim. Dyn. 5, 3237–3260. https://doi.org/10.1007/s00382-014-2418-8

Meadow, A.M., Ferguson, D.B., Guido, Z., Horangic, A., Owen, G., Wall, T., 2015. Moving toward the Deliberate Coproduction of Climate Science Knowledge. Weather. Clim. Soc. 7, 179–191. https://doi.org/10.1175/WCAS-D-14-00050.1

Medellín-Azuara, J., Howitt, R.E., MacEwan, D.J., Lund, J.R., 2011. Economic impacts of climate-related changes to California agriculture. Clim. Change 109, 387–405.

https://doi.org/10.1007/s10584-011-0314-3

Medellín-Azuara, J., Lund, J., Howitt, R., 2015. Jobs per drop irrigating California crops [WWW Document]. Calif. Water Blog. URL http://californiawaterblog.com/2015/04/28/jobs-per-drop-irrigating-california-crops/ (accessed 5.8.15).

Meehan, K., Klenk, N.L., Mendez, F., 2017. The Geopolitics of Climate Knowledge Mobilization. Sci. Technol. Hum. Values 43, 016224391774560. https://doi.org/10.1177/0162243917745601

Mercer, J., Kurvits, T., Kelman, I., Mavrogenis, S., 2014. Ecosystem-based adaptation for food security in the AIMS SIDS: Integrating external and local knowledge. Sustain. 6, 5566–5597. https://doi.org/10.3390/su6095566

Miller, B.W., Symstad, A.J., Frid, L., Fisichelli, N.A., Schuurman, G.W., 2017. Co-producing simulation models to inform resource Management: A case study from southwest South Dakota. Ecosphere 8. https://doi.org/10.1002/ecs2.2020

Mimura, N., Pulwarty, R.S., Duc, D.M., Elshinnawy, I., Redsteer, M.H., Huang, H.Q., Nkem, J.N., Rodriguez, R. a. S., 2014. 15. Adaptation Planning and Implementation. Assess. Rep. 5- Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Part A Glob. Sect. Asp. 869–898. https://doi.org/10.1029/2003JD004173.Aires

Mishler, E.G., 1991. Research Interviewing : Context and Narrative. Harvard University Press, Cambridge, UNITED STATES.

Moss, R.H., Avery, S., Baja, K., Burkett, M., William, S., Chischilly, A.M., Dell, J., Fleming, P.A., Geil, K., Jacobs, K., Jones, A., Knowlton, K., Koh, J., Lemos, M.C., Melillo, J., Pandya, R., Richmond, T.C., Scarlett, L., Snyder, J., Stults, M., Waple, A., Whitehead, J., Zarrilli, D., Ayyub, B., Fox, J., Ganguly, A., Joppa, L., Julius, S., Kirshen, P., Kreutter, R., McGovern, A., Meyer, R., Neumann, J., Solecki, W., Smith, J., Tissot, P., Yohe, G., Zimmerman, R., 2019. Evaluating Knowledge to Support Climate Action: A Framework for Sustained Assessment. Weather. Clim. Soc. https://doi.org/10.1175/WCAS-D-18-0134.1

Mote, P., Brekke, L., Duffy, P.B., Maurer, E., 2011. Guidelines for constructing climate scenarios. Eos (Washington. DC). 92, 257–264. https://doi.org/10.1029/2011EO310001

Mullan, M., Kingsmill, N., Kramer, A.M., Agrawala, S., 2013. National Adaptation Planning: Lessons from OECD Countries, OECD Environment Working Papers. OECD Publishing.

Munang, R., Andrews, J., Alverson, K., Mebratu, D., 2014. Harnessing Ecosystem-based Adaptation To Address the Social Dimensions of Climate Change. Environ. Sci. Policy Sustain. Dev. 56, 18–24. https://doi.org/10.1080/00139157.2014.861676

Munroe, R., Roe, D., Doswald, N., Spencer, T., Möller, I., Vira, B., Reid, H., Kontoleon, A., Giuliani, A., Castelli, I., Stephens, J., 2012. Review of the evidence base for ecosystem-based approaches for adaptation to climate change. Environ. Evid. 1, 13. https://doi.org/10.1186/2047-2382-1-13

National Research Council, 2012. A National Strategy for Advancing Climate Modeling. The National Academy of Sciences. Argonne, IL (United States). https://doi.org/10.2172/1056475

National Research Council, 2009. Informing Decisions in a Changing Climate, Distribution.

Nature (Editorial), 2018. The best research is produced when researchers and communities work together. Nature 562, 7–7. https://doi.org/10.1038/d41586-018-06855-7

Naumann, S., Davis, M., Munang, R., Andrews, J., Thiaw, I., Alverson, K., Mumba, M., Kavagi, L., Han, Z., 2013. The social dimension of ecosystem-based adaptation. Ser. UNEP Policy Ser. Ecosyst. Manag. , Vol. 12.

Nicholas, K.A., Durham, W.H., 2012. Farm-scale adaptation and vulnerability to environmental stresses: Insights from winegrowing in Northern California. Glob. Environ. Chang. 22, 483–494. https://doi.org/10.1016/j.gloenvcha.2012.01.001

Nissan, H., Goddard, L., de Perez, E.C., Furlow, J., Baethgen, W., Thomson, M.C., Mason, S.J., 2019. On the use and misuse of climate change projections in international development. Wiley Interdiscip. Rev. Clim. Chang. e579. https://doi.org/10.1002/wcc.579

Noble, I.R., Huq, S., Anokhin, Y. a., Carmin, J., Goudou, D., Lansigan, F.P., Osman-Elasha, B., Villamizar, a., 2014. 14. Adaptation Needs and Options. Assess. Rep. 5-Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Part A Glob. Sect. Asp. 833–868. https://doi.org/31 March 2014

Ojea, E., 2015. Challenges for mainstreaming Ecosystem-based Adaptation into the international climate agenda, Current Opinion in Environmental Sustainability. https://doi.org/10.1016/j.cosust.2015.03.006

Ortiz, S., 1980. Chapter 8 - Forecasts, Decisions, and the Farmer's Response to Uncertain Environments, in: Barlett, P. (Ed.), Agricultural Decision Making - Anthropological Contributions to Rural Development. Academic Press, pp. 177–202. https://doi.org/http://dx.doi.org/10.1016/B978-0-12-078882-8.50013-1

Pathak, T., Maskey, M., Dahlberg, J., Kearns, F., Bali, K., Zaccaria, D., 2018. Climate Change Trends and Impacts on California Agriculture: A Detailed Review. Agronomy 8, 25. https://doi.org/10.3390/agronomy8030025

Perez, A.A., Fernandez, B.H., Gatti Cazzolla, R., 2010. Building resilience to climate change: Ecosystem-based adaptation and lessons from the field. Gland, Switzerland.

Petersen, C., Holness, S., 2010. World Resources Report case study. South Africa :

Ecosystem-based planning for climate change. Washington DC.

Pielke, R., Prins, G., Rayner, S., Sarewitz, D., 2007. Lifting the taboo on adaptation. Nature 445, 597–598. https://doi.org/10.1038/445597a

Pierce, D.W., Barnett, T.P., Santer, B.D., Gleckler, P.J., 2009. Selecting global climate models for regional climate change studies. Proc. Natl. Acad. Sci. 106, 8441–8446. https://doi.org/10.1073/pnas.0900094106

Pierce, D.W., Cayan, D.R., Dehann, L., 2016. Creating Climate Projections to support the 4th California Climate Assessment. Sacramento, CA. https://doi.org/Docket #: 16-IEPR-04

Pierce, D.W., Cayan, D.R., Maurer, E.P., Abatzoglou, J.T., Hegewisch, K.C., 2015. Improved Bias Correction Techniques for Hydrological Simulations of Climate Change. J. Hydrometeorol. 16, 2421–2442. https://doi.org/10.1175/JHM-D-14-0236.1

Pierce, D.W., Cayan, D.R., Thrasher, B.L., 2014. Statistical Downscaling Using Localized Constructed Analogs (LOCA). J. Hydrometeorol. 15, 2558–2585. https://doi.org/10.1175/JHM-D-14-0082.1

Podesta, G., Letson, D., Messina, C., Royce, F., Ferreyra, R.A., Jones, J., Hansen, J., Llovet, I., Grondona, M., O'Brien, J.J., 2002. Use of ENSO-related climate information in agricultural decision making in Argentina: A pilot experience. Agric. Syst. 74, 371–392. https://doi.org/10.1016/S0308-521X(02)00046-X

Porter, J.J., Dessai, S., 2017. Mini-me: Why do climate scientists' misunderstand users and their needs? Environ. Sci. Policy 77, 9–14. https://doi.org/10.1016/j.envsci.2017.07.004

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food security and food production systems, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1111/j.1728-4457.2009.00312.x

Preston, B.L., Mustelin, J., Maloney, M.C., 2015. Climate adaptation heuristics and the science/policy divide. Mitig. Adapt. Strateg. Glob. Chang. 20, 467–497. https://doi.org/10.1007/s11027-013-9503-x

ProAct network, 2008. The role of environmental management and eco-engineering in disaster risk reduction and climate change adaptation.

Prokopy, L.S., 2014. Agricultural Stakeholders and Their Attitudes towards Climate Change, in: 2014 Extension Energy and Environment Summit. United States Department of Agriculture.

Prokopy, L.S., Carlton, J.S., Haigh, T., Lemos, M.C., Mase, A.S., Widhalm, M., 2017.

Useful to Usable: Developing usable climate science for agriculture. Clim. Risk Manag. 15, 1–7. https://doi.org/10.1016/j.crm.2016.10.004

Prokopy, L.S., Haigh, T., Mase, A.S., Angel, J., Hart, C., Knutson, C., Lemos, M.C., Lo, Y.-J., McGuire, J., Morton, L.W., Perron, J., Todey, D., Widhalm, M., 2013. Agricultural Advisors: A Receptive Audience for Weather and Climate Information? Weather. Clim. Soc. 5, 162–167. https://doi.org/10.1175/WCAS-D-12-00036.1

Reed, M.G., Abernethy, P., 2018. Facilitating Co-Production of Transdisciplinary Knowledge for Sustainability: Working with Canadian Biosphere Reserve Practitioners. Soc. Nat. Resour. 31, 39–56. https://doi.org/10.1080/08941920.2017.1383545

Reed, M.S., 2008. Stakeholder participation for environmental management: A literature review. Biol. Conserv. 141, 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014

Rhoades, A.M., Jones, A.D., Ullrich, P.A., 2018. Assessing Mountains as Natural Reservoirs With a Multimetric Framework. Earth’s Futur. 6, 1221–1241. https://doi.org/10.1002/2017EF000789

Richards, G.W., 2018. The Science–Policy Relationship Hierarchy (SPRHi) model of co-production: how climate science organizations have influenced the policy process in Canadian case studies. Policy Sci. 1–29. https://doi.org/10.1007/s11077-018-9328-2

Roncoli, C., 2006. Ethnographic and participatory approaches to research on farmers’ responses to climate predictions. Clim. Res. 33, 81–99. https://doi.org/10.3354/cr033081

Roncoli, C., Jost, C., Kirshen, P., Sanon, M., Ingram, K.T., Woodin, M., Som??, L., Ouattara, F., Sanfo, B.J., Sia, C., Yaka, P., Hoogenboom, G., 2009. From accessing to assessing forecasts: An end-to-end study of participatory climate forecast dissemination in Burkina Faso (West Africa). Clim. Change 92, 433–460. https://doi.org/10.1007/s10584-008-9445-6

Ruiu, M.L., Maurizi, S., Sassu, S., Seddaiu, G., Zuin, O., Blackmore, C., Roggero, P.P., 2017. Re-staging La Rasgioni: Lessons learned from transforming a traditional form of conflict resolution to engage stakeholders in agricultural water governance. Water (Switzerland) 9. https://doi.org/10.3390/w9040297

Rupp, D.E., Abatzoglou, J.T., Hegewisch, K.C., Mote, P.W., 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest US. J. Geophys. Res. 118, 1–23. https://doi.org/10.1002/jgrd.50843

Safford, H.D., Sawyer, S.C., Kocher, S.D., Hiers, J.K., Cross, M., 2017. Linking knowledge to action: the role of boundary spanners in translating ecology. Front. Ecol. Environ. 15, 560–568. https://doi.org/10.1002/fee.1731

Sierra-Correa, P.C., Cantera Kintz, J.R., 2015. Ecosystem-based adaptation for improving coastal planning for sea-level rise: A systematic review for mangrove coasts. Mar. Policy 51, 385–393. https://doi.org/10.1016/j.marpol.2014.09.013

Siler, N., Kosaka, Y., Xie, S.-P., Li, X., 2017. Tropical Ocean Contributions to California's Surprisingly Dry El Niño of 2015/16. J. Clim. 30, 10067–10079. https://doi.org/10.1175/JCLI-D-17-0177.1

Singh, C., Daron, J., Bazaz, A., Ziervogel, G., Spear, D., Krishnaswamy, J., Zaroug, M., Kituyi, E., 2018. The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. Clim. Dev. 10, 389–405. https://doi.org/10.1080/17565529.2017.1318744

Smit, B., Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability 16, 282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008

Snover, A.K., Mantua, N.J., Littell, J.S., Alexander, M.A., Mcclure, M.M., Nye, J., 2013. Choosing and Using Climate-Change Scenarios for Ecological-Impact Assessments and Conservation Decisions. Conserv. Biol. 27, 1147–1157. https://doi.org/10.1111/cobi.12163

Stadelmann, M., Michaelowa, A., Butzengeiger-Geyer, S., Köhler, M., 2015. Universal Metrics to Compare the Effectiveness of Climate Change Adaptation Projects BT - Handbook of Climate Change Adaptation, in: Leal Filho, W. (Ed.), . Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 2143–2160. https://doi.org/10.1007/978-3-642-38670-1_128

Stavins, R., Zou, J., Brewer, T., Conte Grand, M., den Elzen, M., Finus, M., Gupta, J., Höhne, N., Lee, M.-K., Michaelowa, A., Paterson, M., Kilaparti, R., Wen, G., Wiener, J., Winkler, H., 2015. International cooperation: Agreements & instruments, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stemler, S., 2001. An overview of content analysis. Pract. assessment, Res. Eval. 7, 137–146.

Swart, R., Biesbroek, R., LourenÃ§o, T.C., 2014. Science of adaptation to climate change and science for adaptation. Front. Environ. Sci. 2, 1–8. https://doi.org/10.3389/fenvs.2014.00029

Tall, A., Hansen, J., Jay, A., Campbell, B., Kinyangi, J., Aggarwal, P.K., Zougmoré, R., 2014. Scaling up climate services for farmers: Learning from good practice in Africa and South Asia. Copenhagen. https://doi.org/CCAFS Report No. 13

Tang, S., Dessai, S., 2012. Usable Science? The U.K. Climate Projections 2009 and

Decision Support for Adaptation Planning. Weather. Clim. Soc. 4, 300–313. https://doi.org/10.1175/WCAS-D-12-00028.1

Teutschbein, C., Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies : Review and evaluation of different methods. J. Hydrol. 456–457, 12–29. https://doi.org/10.1016/j.jhydrol.2012.05.052

UCANR, 2018. Tree Selection, The California Backyard Orchard [WWW Document]. URL http://homeorchard.ucanr.edu/The_Big_Picture/Tree_Selection/

UNEP, 2015. Implementation of resolutions adopted by the United Nations Environment Assembly at its first session. Addendum Resolution 1/8: ecosystem-based adaptation. Report of the Executive Director. https://doi.org/10.1080/13880292.2014.987609

UNEP, 2012. Making the Case for Ecosystem-based Adaptation, Building Resilience to Climate Change. Nairobi, Kenya.

UNFCCC, 2016. Progress made in implementing activities under the Nairobi work programme on impacts, vulnerability and adaptation to climate change.

UNFCCC, 2015. Database on Ecosytem based approaches to adaptation [WWW Document]. URL http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/6227.php (accessed 5.8.15).

UNFCCC, 2012. Nairobi work programme on impacts, vulnerability and adaptation to climate change.

UNFCCC, 2011. Ecosystem-based approaches to adaptation: compilation of information. UNFCCC. Bonn, Germany.

United Nations Development Programme, 2006. Adaptation to Climate Change-Responding to Coastline Change in its human dimensions in West Africa through Integrated Coastal Area Management (ACCC).

Van der Hel, S., 2016. New science for global sustainability? The institutionalisation of knowledge co-production in Future Earth. Environ. Sci. Policy 61, 165–175. https://doi.org/10.1016/j.envsci.2016.03.012

Van Epp, M., Garside, B., 2019. Towards an evidence base on the value of social learning-oriented approaches in the context of climate change and food security. Environ. Policy Gov. 118–131. https://doi.org/10.1002/eet.1835

Vano, J.A., Miller, K., Dettinger, M.D., Cifelli, R., Curtis, D., Dufour, A., Olsen, J.R., Wilson, A.M., 2019. Hydroclimatic Extremes as Challenges for the Water Management Community: Lessons from Oroville Dam and Hurricane Harvey. Bull. Am. Meteorol. Soc. 100, S9--S14.

Vaughan, C., Dessai, S., 2014. Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. Wiley Interdiscip. Rev. Clim. Chang. 5, 587–603. https://doi.org/10.1002/wcc.290

Vaughan, C., Dessai, S., Hewitt, C., 2018. Surveying Climate Services: What Can We Learn from a Bird's-Eye View? Weather. Clim. Soc. 10, 373–395. https://doi.org/10.1175/wcas-d-17-0030.1

Vogel, J., Mcnie, E., Behar, D., 2016. Co-producing actionable science for water utilities. Clim. Serv. 2–3, 30–40. https://doi.org/10.1016/j.cliser.2016.06.003

Vogel, J.M., Smith, J.B., O'Grady, M., Flemming, P., Heyn, K., Adams, A., Pierson, D., Brooks, K., Behar, D., 2015. Actionable Science in Practice: Co-producing Climate Change Information for Water Utility Vulnerability Assessments.

Wallis, P.J., Bosomworth, K., Harwood, A., Leith, P., 2017. Charting the emergence of a 'knowing system' for climate change adaptation in Australian regional natural resource management. Geoforum 84, 42–50. https://doi.org/10.1016/j.geoforum.2017.06.002

Walsh, J.E., Chapman, W.L., Romanovsky, V., Christensen, J.H., Stendel, M., 2008. Global climate model performance over Alaska and Greenland. J. Clim. 21, 6156–6174. https://doi.org/10.1175/2008JCLI2163.1

Wamsler, C., 2017. Stakeholder involvement in strategic adaptation planning: Transdisciplinarity and co-production at stake? Environ. Sci. Policy 75, 148–157. https://doi.org/10.1016/j.envsci.2017.03.016

Wamsler, C., 2015. Mainstreaming ecosystem-based adaptation: Transformation toward sustainability in urban governance and planning. Ecol. Soc. 20. https://doi.org/10.5751/ES-07489-200230

Wamsler, C., Pauleit, S., 2016. Making headway in climate policy mainstreaming and ecosystem-based adaptation: two pioneering countries, different pathways, one goal. Clim. Change 137, 71–87. https://doi.org/10.1007/s10584-016-1660-y

WCRP, 2017. CMIP5 - Data Access - Availability [WWW Document]. World Clim. Res. Program. - Coupled Model Intercomp. Proj. C. URL https://cmip.llnl.gov/cmip5/availability.html (accessed 12.17.17).

Weaver, C.P., Mooney, S., Allen, D., Beller-Simms, N., Fish, T., Grambsch, A.E., Hohenstein, W., Jacobs, K., Kenney, M.A., Lane, M.A., Langner, L., Larson, E., McGinnis, D.L., Moss, R.H., Nichols, L.G., Nierenberg, C., Seyller, E.A., Stern, P.C., Winthrop, R., 2014. From global change science to action with social sciences. Nat. Clim. Chang. 4, 656–659. https://doi.org/10.1038/nclimate2319

World Bank, 2009. Convenient Solutions to an Inconvenient Truth : Approaches to Climate Change. Washington DC.

Zhang, Z., 2007. Effective requirements development-A comparison of requirements elicitation techniques. Softw. Qual. Manag. XV Softw. Qual. Knowl. Soc. E. Berki,

J. Nummenmaa, I. Sunley, M. Ross G. Staples Br. Comput. Soc. 225–240.

APPENDIX A: FOR CHAPTER 1

Description of coding methodology

PROJECT DETAILS

Country/ies	Country where the project is located.
Country group	Based on UNFCCC definitions: Least Developed Country **(LDC)**, **Annex I** or **Non-Annex I**
Geographic region	Name of the continent/s where the project is located. If a project is located in multiple continents it is coded as **Multiple**.
Sector targeted for adaptation	Broad sector the project targets, determined by a review of the project description and project activities. Sectors coded include: • **Agriculture** • **Biodiversity conservation** • **Fisheries conservation** • **Forest conservation** • **Marine conservation** • **River management (including wetlands management)** • **Shoreline management (including coastal wetlands management)** • **Urban planning** • **Water management** If the project targets multiple sectors it is coded as **Multi-sector**.
Funding agency	Primary financier of the project, defined as the agency that provided more than 50% of the financing for the project. • **Multilateral Aid**: agencies that operate at the global scale, such as World Bank, UNEP or UNDP. • **Bilateral Aid**: agencies that provide funds from one national government to another, such as the German Federal Environment Ministry (BMU). • **Government:** national or regional governmental agencies funding projects in their own countries. • **NGO:** non-governmental organizations, such as Wetlands International or Nature Conservancy. • **Foundation:** private philanthropic and charitable agencies, such as the Packard Foundation or the McArthur Foundation. • **Private:** private company or individual that is neither a registered foundation nor an NGO, such as Darwin Liquefied Natural Gas Private Limited in Australia.

	• **Unknown:** funding agency type was not identified in the publically available documents.
Project Implementer	Agencies involved in implementation of the project. • **Multilateral Aid**: agencies that operate at the global scale, such as World Bank, UNEP or UNDP. • **Bilateral Aid**: agencies that provide technical assistance from one national government to another, such as the German Federal Environment Ministry (BMU). • **National Government:** national governmental agencies implementing projects in their own countries. • **Sub-National Government:** regional/local governmental bodies implementing projects in their regional locations. • **NGO:** non-governmental organizations, such as Wetlands International or Nature Conservancy. • **Local Communities:** formal or informal community based organizations/groups, or members of the local population in the project location. • **Research Institute:** Agencies (public or private) engaged in research activities such as universities, academic institutes, or research labs. • **Private:** private companies or businesses that are not research institutes or NGOs or local community based organisations.

TYPES OF PROJECT ACTIVITIES

Capacity building	Project activities aim to enhance the ability of individuals, organizations, and institutions to prepare for and respond to climate change. Examples include activities designed to build awareness, provide education or provide training. Coded as **Yes/No**
Climate vulnerability and/or adaptation assessment	Project activities include conducting an analysis of the expected impacts, risks, adaptive capacity, or adaptive options of a region or sector to the effects of climate change. Coded as **Yes/No**
Production of new knowledge	Project activities include the production of new knowledge. Examples include development of planning tools or creation of vulnerability maps. Coded as **Yes/No**
Mainstreaming climate change into planning	Project activities have the explicit goal of facilitating inclusion of climate change issues into planning documents. Coded as **Yes/No**
Development of adaptation policies	Project activities have the explicit goal of developing laws, regulations or policies that will serve to facilitate adaptation. Coded as **Yes/No**
Creation of institutions, networks, or partnerships	Project activities involve the creation of institutions, networks or partnerships to facilitate adaptation**.** Coded as **Yes/No**
Pilot activities	Project activities involve trials or demonstration of adaptation actions. Coded as **Yes/No**
Full-scale implementation	Project activities involve the full-scale implementation of a tangible adaptation intervention. Examples include the planting of mangroves, introducing climate-resilient crop varieties, efficient irrigation practices, etc. Coded as **Yes/No**

ADAPTATION TARGETTING

Climate focus	Project rationale, goal or key objectives* describe combating impacts expected from changes in average climate conditions, such as increased surface temperature, sea level rise, or alterations to the hydrologic cycle as the main motivation. Project activities undertaken support this motivation. **Coded as Yes/No**
Natural hazard focus	Project rationale, goal or key objectives* describe managing impacts of natural hazards such as floods or fires as the main motivation, yet do not focus on the contributions of climate change to natural hazards. Project activities undertaken support this motivation. **Coded as Yes/No**
Development/ Ecosystem focus	Project rationale, goal or key objectives* describe a broad agenda of improving ecosystem or social resilience, such as restoring degraded wetlands, improving food security, or economic development as the main motivation, yet do not focus on the contributions of climate change to ecosystem or social resilience. Project activities undertaken support this motivation. **Coded as Yes/No**
Climate plus other focus	Project rationale, goals or key objectives* explicitly mention responding to the impacts of climate change as well at least one of development, ecosystem resilience, or natural hazard as main motivations. Project activities undertaken support these multiple motivations**. Coded as Yes/No**
Temporal focus	Time scale of climatic conditions considered. • **Future climate change:** project documentation describes the project as addressing the impacts of future changes to climate, whether or not it also describes the project as addressing current climate variability. • **Current climate adaptation deficits:** project documentation describes the project as addressing adaptation deficits associated with current climate variability yet does not explicitly describe how the project will address future climate change.

* Where the project rationale, goals or key objectives were vague, the specific activities undertaken by the project were analyzed to assess the project's main motivation.

INFORMATION ON CLIMATE CHANGE AND IMPACTS

Expected future climatic conditions	Depth of climatic information used in the project design. • **No projections:** project documentation includes no mention of expected future climate. • **Simple macro-scale:** project documentation includes or refers to simple, macro-scale projections of future climate change such as expected average annual temperature rise or average increase/decrease in annual precipitation for the country in which the project is located. • **Detailed regional – prior studies:** project documentation includes or refers to information from previous studies that include detailed projections for the region, such predictions of changes in seasonal precipitation or in the frequency of extreme events. • **Detailed regional –part of project:** project activities include the development of detailed regional-scale information, such as predictions of changes in seasonal precipitation or in the frequency of extreme events.
Expected sectoral impacts	Project documentation includes or refers to detailed assessments of how expected changes in climate will translate into specific sectoral impacts. Coded as **Yes/No**

INFORMATION ON ADAPTATION EFFECTIVENESS

Timeframe of impacts	Project documentation addresses the time frame under which climate change will be experienced. Coded as **Yes/No**
Timeframe for adaptation effectiveness	Project documentation addresses the time required for the adaptation reach effectiveness. Coded as **Yes/No**
Climatic conditions for adaptation benefits	Project documentation addressed the range of climatic conditions under which the adaptation intervention will provide benefits. Coded as **Yes/No**
Scale of intervention	Project documentation addresses the size or magnitude of the adaptation needed to provide adaptation benefits, such as hectares of saltmarsh that would need to be restored to adapt to erosion due to future sea-level rise. Coded as **Yes/No**

Acknowledged uncertainty broadly	Project documentation mentions uncertainty broadly in expected future climate, in expected sectoral impacts, or in the long-term performance of the adaptation actions. Coded as **Yes/No**

INFORMATION ON MALADAPTATION

Acknowledged	Project documentation discussed either the potential for maladaptation, for unintended negative impacts, or risks from the project. Coded as **Yes/No**
Avoided	Project documentation indicates that project activities aim to avoid past, current or future maladaptive practices. Coded as **Yes/No**
No mention	Project documentation does not address maladaptation or potential unintended negative impacts of the project. Coded as **Yes/No**

DETERMINING PROJECT BENEFITS

Tracking metrics	Metrics used to track implementation and outcomes from the project. • **Progress only:** at least 25% of a project's activities are monitored through a metric/s that track the progress in implementation of specific actions undertaken. • **Effectiveness only:** at least 25% of a project's activities are monitored through a metric/s that track the efficacy of the adaptive action. • **Progress and effectiveness:** at least 25% of a project's activities are monitored using both progress and effectiveness metrics. • **No metrics:** less than 25% of the project's activities are monitored using either progress or effectiveness metrics. • **Not enough information:** project documentation does not provide sufficient details to analyze the metrics used for monitoring and evaluation. • **N/A:** project activities do not lend themselves to monitoring and evaluation metrics. Examples of such activities include the collection of climate data or the assessment of climate vulnerability.

Long-term adaptation benefits	Methods used to link implementation of project activities to long-term adaptation benefits. • **Quantitative:** project documentation uses quantitative analyses, such as cost benefit analysis, to link implementation of project activities to long-term adaptation benefits. • **Qualitative:** project documentation draws from prior research or academic publications on the performance of adaptation measures to qualitatively link implementation of project activities to long-term adaptation benefits. • **No link:** project documentation does not link implementation of project activities to long-term adaptation benefits. • **Not enough information:** project documentation does not provide sufficient details to code the link between implementation of project activities and long-term adaptation benefits. • **N/A:** project activities do not lend themselves to monitoring and evaluation metrics.
Long-term monitoring	Project activities include concrete steps to monitor the impacts of implementing the project for durations of 10 years or more. Coded as **Yes/No**

Reference information for EbA projects analyzed

Project # 1: Responding to shoreline change and its human dimensions in West Africa through integrated coastal area management.

- United Nations Development Programme. (2006). Adaptation to climate change- Responding to coastline change in its human dimensions in West Africa through integrated coastal area management (ACCC). http://adaptation-undp.org/resources/prodocs/re-submission-waf-project-document-24-april-2006-part-1. Accessed 15 November 2014

Project # 2: Community based fire management in Australia.

- ProAct Network. (2008b). The role of environmental management in disaster risk reduction and climate change adaptation, Annex I, case studies. http://www.unisdr.org/files/4148_em.report.annex1.pdf. Accessed 15 November 2014

Project # 3: The protective capacity of forests against snow.

- ProAct Network. (2008a). The role of environmental management and eco-engineering in disaster risk reduction and climate change adaptation. http://www.unisdr.org/files/4148_emecoengindrrcca1.pdf . Accessed 15 November 2014
- ProAct Network. (2008b). The role of environmental management in disaster risk reduction and climate change adaptation, Annex I, case studies. http://www.unisdr.org/files/4148_em.report.annex1.pdf . Accessed 15 November 2014

Project # 4: Enhancing adaptive capacity in semi-arid mountainous regions, Bolivia.

- Gonzales, J., Aparicio, M., Cusicanqui, J., Dougherty, W., & Devisscher, T. (2006). Building adaptive capacity in two vulnerable semi-arid mountainous regions in Bolivia. https://www.weadapt.org/sites/weadapt.org/files/legacy-new/knowledge-base/files/4dac10943882aBolivia_NCAP.pdf . Accessed 15 November 2014

Project # 5: Carpathian integrated assessment of vulnerability to climate change and ecosystem-based adaptation measures (CARPIVIA) project.

- DLO-Alterra Wageningen UR. (2014). Draft final report CARPIVIA project - Revised assessment of vulnerability and potential adaptation measures. Wageningen. https://dl.dropboxusercontent.com/u/3951461/2014_CARPIVIA_draftfinalreport.pdf . Accessed 15 November 2014

Project # 6: The Ceiba-Pilares project.

- BirdLife International. (n.d.-a). La Ceiba-Pilares project. http://www.unep.org/climatechange/adaptation/Portals/133/documents/Session1/6Peru_MelanieHeath.pdf . Accessed 15 November 2014
- BirdLife International. (n.d.-b). La Ceiba-Pilares project. Quito-Ecuador. http://www.birdlife.org/downloads/america/files/Flder_Tumbes_La Ceiba_En.pdf . Accessed 15 November 2014
- BirdLife International. (2009b). Partners with nature: How healthy ecosystems are helping the world's most vulnerable adapt to climate change. http://www.birdlife.org/sites/default/files/attachments/Ecosystemsandadaption_0.pdf . Accessed 15 November 2014
- Nature and Culture International. (n.d.). Sustainable development through the La Ceiba-Pilares project. Retrieved February 1, 2015, from http://www.naturalezaycultura.org/concept/htm/peru/areas-dryforest-ceibapilares.htm

Project # 7: Coping with drought and climate change in the Chiredzi district.

- United Nations Development Programme. (2012b). Terminal evaluation of coping with drought and climate change in Zimbabwe. http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/MandE/EO_TEs_FY13/UNDP_TEs_APR2013/3156_UNDP_TE/3156_UNDP_TE_Final_TE_Report_-_August_29.doc . Accessed 15 November 2014

Project # 8: Integrated national adaptation plan - Colombia highland ecosystems.

- The World Bank. (2006). Colombia INAP GEF project document. http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/Climate Change/Colombia Integrated National Adaptation Plan/Colombia INAP GEF Project Document.doc . Accessed 15 November 2014
- The World Bank. (2012). Implementation completion and results report: Report No: ICR2298. http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/MandE/EO_TEs_FY13/WorldBank_TEs_APR2013/2019_WB_TE_P083075-ICR_Colombia.pdf . Accessed 15 November 2014

Project # 9: Edmonton's urban forest management plan (UFMP).

- The City of Edmonton. (2012). Urban forest management plan - Edmonton's urban forest - Taking root today for a sustainable tomorrow. http://www.edmonton.ca/residential_neighbourhoods/PDF/Urban_Forest_Management_Plan.pdf . Accessed 15 November 2014

Project # 10: Drought-resistant agriculture in El-Salvador.

- International Federation of Red Cross and Red Crescent Societies. (n.d.). Case study drought in El Salvador: Response and mitigation. https://www.ifrc.org/Global/Case studies/Disasters/cs-elsalvador.pdf . Accessed 15 November 2014

Project # 11: Managed realignment and the reestablishment of saltmarsh habitat, Freiston shore, U.K.

- Freiston Shore Environment Agency. (2008). Freiston shore managed realignment site -IS001/W/2008. http://www.channelcoast.org/anglia/analysis_programme/Freiston Shore, Freiston Shore managed realignment site (Information sheet no.1 (April 2008)) IS001W2008.pdf. Accessed 15 November 2014
- ProAct Network. (2008b). The role of environmental management in disaster risk reduction and climate change adaptation, Annex I, case studies. http://www.unisdr.org/files/4148_em.report.annex1.pdf . Accessed 15 November 2014

Project # 12: Agriculture in the lower Flint river basin, Georgia, USA.

- National Association of Conservation Districts. (n.d.). Our land, our water: Case studies in locally led successes. Madison, Wisconsin. http://www.nacdnet.org/resources/reports/our_land_our_water.pdf . Accessed 15 November 2014
- Reckford, D., Perry, C., Rad, Y., Jim, M., David, W., Wilson, F., … Marty, M. (n.d.). Agricultural water conservation in the lower Flint river basin. https://www.conservationgateway.org/Documents/AG Water Conservation - Lower Flint GA.pdf . Accessed 15 November 2014
- Watson, R., & Scarborough, B. (n.d.). Flint river basin irrigation: Wireless water for biodiversity. Bozeman, MT. http://www.perc.org/sites/default/files/pdfs/flint_river_cs.pdf . Accessed 15 November 2014

Project # 13: Community-based coastal habitat restoration ('Green coast project').

- Koning, P. De, & Sachithanandam, S. (2008). Green coast: For nature and people after the tsunami - End term evaluation. https://cmsdata.iucn.org/downloads/green_coast_project___final_evaluation_2008.pdf . Accessed 15 November 2014
- Wibisono, I. T. C., & Sualia, I. (2008). Final Report: An assessment of lessons learnt from the "Green coast project" in Nanggroe Aceh Darussalam (NAD)

province and Nias island, Indonesia, period 2005-2008. Bogor. http://www.wetlands.org/LinkClick.aspx?fileticket=8c5dU0zkE6s%3D&tabid=56 . Accessed 15 November 2014

Project # 14: Integrating agro-forestry practices in the farming system in Grenada.

- Roberts, D. A., & Shears, R. (2008). Good agricultural practices for climate risk management in Grenada - Summary report. http://www.fao.org/fileadmin/templates/tc/tce/pdf/Grenada_draft_final_report_May_2008.pdf . Accessed 15 November 2014

Project # 15: Integration of climate change risk and resilience into forestry management (ICCRIFS).

- United Nations Development Programme. (2010b). Integration of climate change risks and resilience into forestry management in Samoa (ICCRIFS). http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/Climate Change/Samoa - (4216) - Integration of Climate Change Risk and Resilience/02-12-2011 ID4216 Council. Letter pdf.pdf . Accessed 15 November 2014

Project # 16: Jordan valley permaculture project.

- ProAct Network. (2008b). The role of environmental management in disaster risk reduction and climate change adaptation, Annex I, case studies. http://www.unisdr.org/files/4148_em.report.annex1.pdf . Accessed 15 November 2014

Project # 17: Kikuyu escarpment forest.

- BirdLife International. (2009b). Partners with nature: How healthy ecosystems are helping the world's most vulnerable adapt to climate change. http://www.birdlife.org/sites/default/files/attachments/Ecosystemsandadaption_0.pdf . Accessed 15 November 2014
- Buck, L. E., Wallace, C., Milder, J. C., & Kuria, D. (n.d.). Advancing and balancing ecological conservation, agricultural production and local livelihood goals in Kenya's Kikuyu escarpment landscape. http://legacy.ecoagriculture.org/documents/files/doc_400.pdf . Accessed 15 November 2014
- United Nations Development Programme. (n.d.-a). Conservation and sustainable use of the Kikuyu escarpment forests. http://sgp.undp.org/index.php?option=com_docman&Itemid=188&task=doc_download&gid=48 . Accessed 15 November 2014

Project # 18: Kimbe bay: Scientific design of a resilient network of marine protected areas.

- Colls, A., Ash, N., & Ikkala, N. (2009). Ecosystem-based adaptation: A natural response to climate change. https://cmsdata.iucn.org/downloads/iucn_eba_brochure.pdf . Accessed 15 November 2014
- Green, A., Lokani, P., Sheppard, S., Almany, J., Keu, S., Aitsi, J., … Lipsett-Moore, G. (2007). Scientific design of a resilient network of marine protected areas Kimbe bay , West New Britain , Papua New Guinea. http://www.reefresilience.org/pdf/Kimbe_Complete_Report.pdf . Accessed 15 November 2014

Project # 19: Assessing the impacts of climate change on Madagascar's biodiversity and livelihoods.

- Conservation International. (2008). Assessing the impacts of climate change on Madagascar 's biodiversity and livelihoods. http://marineclimatechange.com/marineclimatechange/Madagascar_files/CI-WWF Madagascar Workshop Report FINAL.pdf . Accessed 15 November 2014
- Perez, A. A., Fernandez, B. H., & Gatti Cazzolla, R. (2010). Building resilience to climate change: Ecosystem-based adaptation and lessons from the field. Gland, Switzerland. http://www.gwp.org/Global/ToolBox/References/Building resilience to climate change (IUCN, 2010).pdf . Accessed 15 November 2014

Project # 20: Using the maya nut tree to increase tropical agroecosystem resilience to climate change in Central America and Mexico.

- Buffle, P., & Vohman, E. (n.d.). Using the maya nut tree to increase tropical agroecosystem resilience to climate change in Central America and Mexico. http://infoagro.net/archivos_Infoagro/Regatta/biblioteca/EN_maya_nut_0.pdf . Accessed 15 November 2014
- Buffle, P., & Vohman, E. (2011). Using the maya nut tree to increase tropical agroecosystem resilience to climate change in Central America and Mexico. Mother Pelican: A Journal of Sustainable Human Development, 7(12). http://www.pelicanweb.org/solisustv07n12page8.html
- United Nations Environment Programme. (2012a). Global environment outlook : Policy options for Latin America and the Caribbean. http://www.unep.org/geo/pdfs/geo5/Brief_Ecosystem Approach_biodiversity.pdf . Accessed 15 November 2014

Project # 21: Adapting to climate change in the Mesoamerican reef.

- Bood, N. D. (2008). Enabling adaptation to climate change within the Mesoamerican reef: A case study. http://assets.panda.org/downloads/wwf_enabling_adaptation_to_climate_booklet_draft.pdf . Accessed 15 November 2014

Project # 22: Coping with drought and climate change, Mozambique.

- United Nations Development Programme. (2005). Coping with drought and climate change - Request for GEF funding. http://www.undp-alm.org/sites/default/files/downloads/resubmission_moz_cwd_nov_1.doc . Accessed 15 November 2014
- United Nations Development Programme. (2010a). Coping with drought and climate change in Mozambique. http://www.undp-alm.org/sites/default/files/downloads/alm_case_study_mozambique_february_2011_final.pdf . Accessed 15 November 2014
- United Nations Development Programme. (2012a). Coping with drought and climate change. Accessed 15 November 2014

Project # 23: Nagoya water revitalisation plan.

- Kazmierrczak, A., & Carter, J. (2010). Adaptation to climate change using green and blue infrastructure. A database of case studies. http://www.grabs-eu.org/membersArea/files/nagoya.pdf . Accessed 15 November 2014

Project # 24: New Orleans: Preserving the wetlands to increase climate change resilience.

- Kazmierrczak, A., & Carter, J. (2010). Adaptation to climate change using green and blue infrastructure. A database of case studies. http://www.grabs-eu.org/membersArea/files/nagoya.pdf . Accessed 15 November 2014

Project # 25: Nomadic herders: Enhancing the resilience of pastoral ecosystems and livelihoods.

- GRID-Arendal. (2012). Nomadic herders. http://reindeerherding.org/wp-content/uploads/2013/01/nomadic-herders-2-pager-090312.pdf . Accessed 15 November 2014
- United Nations Environment Programme. (2012b). Nomadic herders project-Project identification form. http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/Multi Focal Area/Regional - (4764) - Enhancing the Resilience of Pastoral Ecosystems an/4-6-12 - Rev PIF doc.docx.pdf. Accessed 15 November 2014

Project # 26: Netherlands Ooijpolder 'climate buffer' project.

- ARK Nature, Natuurmonumenten, National Forest Service, Bird Life International - The Netherlands, Wadden Sea Society, & Landschappen, D. (2014). Natural climate proof Netherlands. Retrieved January 1, 2014, from http://www.klimaatbuffers.nl/climate-buffers
- BirdLife International. (2009a). A landscape approach to conservation can help tackle climate change. Retrieved January 1, 2014, from http://www.birdlife.org/datazone/sowb/casestudy/286
- BirdLife International. (2009b). Partners with nature: How healthy ecosystems are helping the world's most vulnerable adapt to climate change. http://www.birdlife.org/sites/default/files/attachments/Ecosystemsandadaption_0.pdf . Accessed 15 November 2014

Project # 27: Orito Ingi Ande medicinal plants sanctuary.

- IUCN. (2008). The national natural park system of Colombia reaches 54 protected areas. http://www.iucn.org/about/work/programmes/gpap_home/gpap_news/?1143/The-National-Natural-Park-System-of-Colombia-reaches-54-protected-areas . Accessed 15 November 2014
- Londono, J. M. (n.d.). Indigenous people, culture, health and biodiversity: Introducing a new protection approach at the sanctuary of flora medicinal plants Orito Ingi Ande. https://www.cbd.int/cooperation/pavilion/nagoya-presentations/2010-10-19-session1-Fernanda-en.pdf . Accessed 15 November 2014
- National Natural Parks of Colombia. (n.d.). Orito Ingi Ande. Retrieved January 1, 2014, from http://www.parquesnacionales.gov.co/PNN/portel/libreria/php/decide.php?patron=02.0135

Project # 28: The Pangani river basin management project (PRBMP).

- IUCN. (n.d.-a). Climate change adaptation in the Pangani river basin - Brief published by the Pangani river basin management project. https://cmsdata.iucn.org/downloads/brief_1___climate_change.pdf . Accessed 15 November 2014
- Pangani River Basin Management Project. (n.d.-a). Mid-term review of the Pangani river basin management project. http://www.undp-alm.org/sites/default/files/downloads/tanz_-_pangani_river_basin_management_project_1.pdf . Accessed 15 November 2014
- Pangani River Basin Management Project. (n.d.-b). The Pangani river basin management project. https://cmsdata.iucn.org/downloads/brief_9___the_pangani_river_basin_management_project_240411_2.pdf . Accessed 15 November 2014

- PBWO, & IUCN. (2009). Final project report. Pangani basin water board, Moshi and IUCN eastern & southern Africa regional Pprogram. https://cmsdata.iucn.org/downloads/final_project_summary_report.pdf . Accessed 15 November 2014

Project # 29: Rio de Janeiro's community reforestation project.

- The Mega Cities Project, & The Brazilian Institute of Municipal Administration. (1994). Paid self-help reforestation project Rio de Janeiro. http://www.megacitiesproject.org/pdf/reforestation.pdf . Accessed 15 November 2014
- UNFCCC. (n.d.). Community reforestation in Rio de Janeiro, Brazil. Retrieved January 1, 2014, from http://maindb.unfccc.int/public/adaptation/adaptation_casestudy.pl?id_project=139

Project # 30: Ecosystem-based adaptation by small-holder farmers in Roslagen, Sweden.

- Colls, A., Ash, N., & Ikkala, N. (2009). Ecosystem-based adaptation: A natural response to climate change. https://cmsdata.iucn.org/downloads/iucn_eba_brochure.pdf . Accessed 15 November 2014
- Tengo, M., & Belfrage, K. (2004). Local management practices for dealing with change and uncertainty: A cross-scale comparison of cases in Sweden and Tanzania. Ecology and Society, 9(3), -. doi:http://www.ecologyandsociety.org/vol9/iss3/art4

Project # 31: Conservation and management of high altitude peatlands of Ruoergai marshes for water security and climate change adaptation.

- United Nations Development Programme. (2009). Terminal evaluation report - Wetland biodiversity conservation and sustainable use in China. https://erc.undp.org/evaluationadmin/downloaddocument.html?docid=3544 . Accessed 15 November 2014
- Wetlands International. (n.d.). Wetlands and climate change adaptation - Sustaining and restoring wetlands: an effective climate change response. http://www.wetlands.org/Portals/0/publications/Count Form/Brochure/triplet_adaptation_1109_lowres.pdf . Accessed 15 November 2014
- Wetlands International. (2005). Ruoergai high altitude peatlands. http://www.wetlands.org/Portals/0/publications/Factsheet/FactSheet_Ruoergai.pdf . Accessed 15 November 2014

- Wetlands International. (2010). Biodiversity loss and the global water crisis. Wageningen. https://www.cbd.int/iyb/doc/prints/iyb-netherlands-watercrisis.pdf . Accessed 15 November 2014

Project # 32: Maintenance of hydropower potential in Rwanda through ecosystem restoration.

- Hove, H., Parry, J.-E., & Lujara, N. (2010). World resources report case study. Maintenance of hydropower potential in Rwanda through ecosystem restoration. Washington DC. http://www.wri.org/sites/default/files/wrr_case_study_ecosystem_restoration_rwanda.pdf . Accessed 15 November 2014
- World Resources Institute, United Nations Development Programme, & The World Bank. (2011). World resources 2010–2011: Decision making in a changing climate - Adaptation challenges and choices. Washington DC. http://pdf.wri.org/world_resources_report_2010-2011.pdf . Accessed 15 November 2014

Project # 33: South Africa: Ecosystem-based planning for climate change.

- Petersen, C., & Holness, S. (2010). World resources report case study. South Africa : Ecosystem-based planning for climate change. Washington DC. http://www.wri.org/sites/default/files/uploads/wrr_case_study_south_africa_ecosystem_based_planning.pdf . Accessed 15 November 2014
- World Resources Institute, United Nations Development Programme, & The World Bank. (2011). World resources 2010–2011: Decision making in a changing climate - Adaptation challenges and choices. Washington DC. http://pdf.wri.org/world_resources_report_2010-2011.pdf . Accessed 15 November 2014

Project # 34: Community-based rangeland rehabilitation.

- Ministry of Agriculture Natural and Animal Resources Sudan. (1994). Project brief for the programme review committee: Community based rangeland rehabilitation for carbon sequestration and biodiversity. http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/Climate Change/Sudan - Community Rangeland Carbon Sequestration/Project Brief.pdf. Accessed 15 November 2014
- United Nations Development Programme. (n.d.-b). Sudan - Community based rangeland rehabilitation for carbon sequestration and biodiversity. http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/Climate Change/Sudan - Community Rangeland Carbon Sequestration/Sudan - Rangeland Carbon Sequestration Project Doc.pdf. Accessed 15 November 2014
- United Nations Development Programme. (2003). GEF Secretariat terminal evaluation review - Sudan - Community based rangeland rehabilitation for carbon

sequestration and biodiversity. http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/M&E/Documents and data/DatabaseContent/TE/2001 (January) to end of FY 2002/Terminal Evaluation Reviews/Climate Change/377 Sudan - Community Rangeland Rehab for Carbon Seq Bio.xls. Accessed 15 November 2014

Project # 35: Adaptation to climate change impacts in the Syunik mountain forest ecosystems of Armenia.

- United Nations Development Programme. (2007). Adaptation to climate change impacts in mountain forest ecosystems of Armenia - Request for project preparation grant. Accessed 15 November 2014
- United Nations Development Programme. (2008). Project document PIMS 3814 PIMS 3814 : Adaptation to climate change in mountain forest ecosystems of Armenia. http://www.undp.org/content/dam/armenia/docs/FA_Prodoc_2008.pdf . Accessed 15 November 2014

Project # 36: Increasing taro crop diversity.

- Moorhead, A. (2011). Lessons in diversity from Samoa's taro blight. http://aciar.gov.au/files/node/13748/lesson_in_diversity_from_samoa_s_taro_blight_95850.pdf . Accessed 15 November 2014
- Taylor, M., & Iosefa, T. (2013). Taro leaf blight manual. http://www.spc.int/lrd/publications/doc_download/2200-taroleafblightmanual . Accessed 15 November 2014

Project # 37: Tonle Sap.

- Cambodia Climate Change Alliance. (2013). Integrating climate change resilience, livelihoods and floodplain management for the Tonle Sap. http://www.camclimate.org.kh/en/documents-and-media/library/category/69-second-call-projects.html?download=231:ci-7-2-2013 . Accessed 15 November 2014
- Conservation International. (2011b). Vulnerability assessment, adaptation planning and pilot activities in Cambodia's Tonle Sap lake region. Cambodia. http://www.conservation.org/publications/documents/CI_Cambodia_NWP_Submission_Vulnerability_Assessment_Adaptation_Planning_Pilot_Activities_Tonle_Sap_Lake.pdf . Accessed 15 November 2014

Project # 38: Whangamarino wetlands.

- Robertson, H., & Suggate, R. (2011). Arawai Kākāriki Wetland restoration programme 2007 – 2010 implementation report. Wellington. http://www.doc.govt.nz/Documents/conservation/land-and-freshwater/wetlands/arawai-kakariki-implementation-report.pdf . Accessed 15 November 2014

- Sullivan, W., Robertson, H., Clucas, R., Cook, L., & Lange, K. (2011). Arawai Kākāriki Wetland restoration programme - Whangamarino outcomes report 2007-2011. http://www.doc.govt.nz/Documents/conservation/land-and-freshwater/wetlands/whangamarino-outcomes-report.pdf . Accessed 15 November 2014

Project # 39: Climate change governance capacity: Building regionally and nationally tailored ecosystem-based adaptation in Mesoamerica.

- IUCN. (n.d.-b). Ecosystem based adaptation highlights - Improving livelihoods and water governance in Mesoamerica. https://cmsdata.iucn.org/downloads/ecosystem_based_adaptation__english__baja_1.pdf . Accessed 15 November 2014
- Sanchez, J. C., & Roberts, J. (2014). Transboundary water governance. Adaptation to climate change. Gland, Switzerland. https://portals.iucn.org/library/efiles/documents/IUCN-EPLP-no.075.pdf . Accessed 15 November 2014

Project # 40: Ecosystem-based adaptation in marine, terrestrial and coastal regions as a means of improving livelihoods and conserving biodiversity in the face of climate change.

- Ancois, de V. (2013). Ecosystem-based adaptation to climate change in Namaqualand, South Africa - Cost-effectiveness of rangeland rehabilitation for erosion control. http://www.conservation.org/publications/Documents/CI_Ecosystem-based-Adaptation-South-Africa-Cost-Effectiveness-Rangeland-Report.pdf . Accessed 15 November 2014
- Boquiren, R., Carlo, G. Di, & Quibilan, M. . (2010). Climate change vulnerability assessment of the Verde island passage, Philippines. Arlington, Virginia. http://ian.umces.edu/pdfs/ian_report_315.pdf . Accessed 15 November 2014
- Bourne, A., Donatti, C., Holness, S., & Midgley, G. (2011). Climate change vulnerability assessment for the Namakwa district municipality. http://www.conservation.org/global/ci_south_africa/publications/Documents/Vulnerability Assessment Full Technical Report - NDM.pdf. Accessed 15 November 2014
- Conservation International. (n.d.-c). Ecosystem-based adaptation for terrestrial , marine and coastal regions. Arlington, Virginia. http://www.conservation.org/publications/documents/CI_IKI_Ecosystem-based_Adaptation_Factsheet.pdf . Accessed 15 November 2014
- Conservation International. (2011a). Ecosystem-based Adaptation (EbA) in marine, terrestrial and coastal regions as a means of improving livelihoods and conserving biodiversity in the face of climate change.

http://unfccc.int/resource/docs/2011/smsn/ngo/337.pdf . Accessed 15 November 2014

- Hole, D. (2012). EbA – Building the evidence base. Accessed 15 November 2014
- Pereira, R., Donatti, C. I., Nijbroek, R., Pidgeon, E., & Hannah, L. (2013). Climate Change vulnerability assessment of the Discovery coast and Abrolhos shelf, Brazil. http://www.conservation.org/publications/Documents/CI_Ecosystem-based-Adaptation-Vulnerability-Assessment-Brazil.pdf . Accessed 15 November 2014

Project # 41: Ecosystem-based adaptation for smallholder subsistence and coffee farming communities in Central America.

- CATIE, & Conservation International. (2012). Ecosystem-based adaptation for smallholder subsistence and coffee farming communities in Central America. Accessed 15 November 2014
- Conservation International. (n.d.-a). Climate change research: Ecosystem-based adaptation for smallholder subsistence and coffee farming communities in Central America. Accessed 15 November 2014
- Conservation International. (n.d.-b). Ecosystem-based adaptation for smallholder subsistence and coffee farming communities in Central America (CASCADE). http://www.surveycto.com/images/case_downloads/CASCADE-Brochure-English.pdf . Accessed 15 November 2014

Project # 42: Choiseul province climate change vulnerability and adaptation assessment report.

- Mataki, M., Solo, G., Donohoe, P., Alele, D., & Sikajajaka, L. (2013). Choiseul province climate change vulnerability and adaptation assessment report. https://www.sprep.org/attachments/Publications/ChoiseulCCAssmntreport.pdf . Accessed 15 November 2014

Project # 43: A comparative analysis of EbA and engineering options for Lami town, Fiji.

- Rao, N. S., Carruthers, T., Anderson, P., Sivo, L., Saxby, T., Trevor, D., … Chape, S. (2012). A comparative analysis of ecosystem–based adaptation and engineering options for Lami town, Fiji. A synthesis report by the secretariat of the Pacific regional environment programme. Apia, Samoa. http://ian.umces.edu/pdfs/ian_report_382.pdf . Accessed 15 November 2014
- Rao, N. S., Carruthers, T., Anderson, P., Sivo, L., Saxby, T., Trevor, D., … Chape, S. (2013). An economic analysis of ecosystem-based adaptation and engineering options for climate change adaptation in Lami town, Republic of the Fiji Islands. Apia, Samoa. http://ian.umces.edu/pdfs/ian_report_392.pdf . Accessed 15 November 2014

APPENDIX B: FOR CHAPTER 2

Chapter 2.2

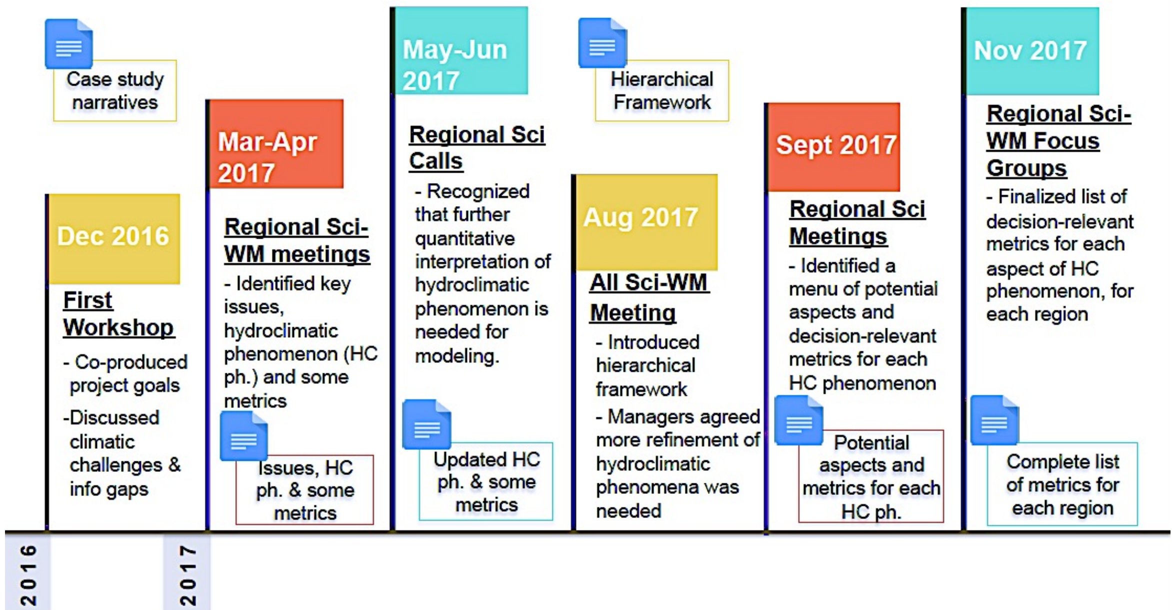

Figure B. 1: Timeline of Key Engagements. The figure provides a chronological illustration of key engagement activities, along with their goals and motivations at each stage. Scientists are denotes as 'Sci', water managers as 'WM', and hydroclimatic phenomena as 'HC ph.'.

CALIFORNIA				
Issue	**Hydroclimatic Phenomenon**	**Aspect of Phenomenon**	**Decision-relevant Metric**	**Decision/Use**
Water Supply	Snowpack	Annual cycle of snow accumulation and melt	Snow Water Equivalent (SWE) triangle - Peak snow (amount and timing), and its relationship with average snow-accumulation and -melt rates, and timing and length of accumulation and melt seasons	On-stream reservoir management, and understanding future streamflow characteristics - Shape of the triangle shows the changing dynamics of the snow season, and what to expect in terms of runoff timing and amounts.

Floods	Snowmelt	Peak Snowmelt {Pulse events}	Highest melt rate and its timing and rate of occurrence	Reservoir operations and flood management.
Water Supply	Snowpack	Inter-annual Variability in Snowpack	Deviations from historical mean in SWE, Snowpack and Snowmelt (amount and timing)	Multi-year water supply planning and drought preparedness.
Floods	Streamflow	Peakflow {Pulse events}	Frequency of Rain-on-snow events and magnitude of associated run-off	Reservoir operations and flood management.
Water Supply	Rainfall	Annual cycle of Rainfall	Rainfall 'geometry' (like SWE triangle) Including start date, length and magnitude of wet season & dry season.	Multi-year supply planning, reservoir operations management, and estimating water demands.
Water Supply	Rainfall	Monthly Rainfall	% distributions of annual rainfall among different months (for specific time-periods 2030, 2060 and 2100)	Seasonal water supply planning, and reservoir operations management.
Floods	Rainfall	Extreme Rainfall	IDF curves, specifically values for 5,10, 25, 100 year, 1-day storms.	Flood and stormwater management.
Water Supply	Streamflow	Seasonal Streamflow amount (in snowmelt season)	Cumulative run off on July 1	Annual water supply planning for the year is based on July 1 reservoir level estimates (i.e. July 1 is the baseline).
Water Supply	Streamflow	Low-end Streamflow	Annual 7-day low flow	Water quality management (issuing discharge permits), and planning water supply during dry years (determining permit limits for water withdrawals).

Water Supply	Streamflow	Streamflow Timing	Timing of center of mass	Water supply planning for time-sensitive uses (crops, timed water diversions, water ecosystems).
Floods	Streamflow	Peakflow	1-, 3-, 7-, 15-, 30-, 60-day maximum inflow volumes (design maximum flows)	Reservoir management of high flows, and flood control.
Floods	Streamflow	Peakflow	Volume-duration-frequency curves {for longer duration wet periods 3- day, 7-day, 10-day etc.}	Reservoir management of high flows, and flood control.
Water Supply	Streamflow	Demand-Supply gap in Streamflow	Streamflow curves showing the general shape and timing of runoff supply and water demand, and the differential (or gap) between the two	Water demand and supply planning.
Water Supply	Streamflow	Inter-annual variability	Deviation from historical annual mean in true natural flow (unimpaired runoff)	Water supply planning and use of supplemental water supplies.
Water Supply	Droughts/dry spells	Water year types	Probability of specific sequences of water year types based on Department of Water Resources (DWR's) classification, (e.g. 8 consecutive dry years)	Water planning decisions including water rights and restrictions. Systems and operations are designed around worst case "design droughts" with specific historic sequences in mind.
Water Supply	Droughts/dry spells	Extreme temperature	Average daily maximum temperature	Water demand projections.
Water Supply	Droughts/dry spells	Extreme temperature	Number of days over 100°F	Water demand projections.

Water Supply	Droughts/dry spells	Extreme temperature	Number of days in a year when the daily maximum temperature exceeds the 98th historical percentile of daily maximum temperatures between April and October.	Water demand projections.

COLORADO

Issue	**Hydroclimatic Phenomenon**	**Aspect of Phenomenon**	**Decision-relevant Metric**	**Decision/Use**
Water Supply	Streamflow	Seasonal Streamflow amount (in snowmelt season)	Cumulative run-off from April-July (Reservoir in-flow estimates)	Water supply planning in terms of forecasted water volumes.
Water Supply	Streamflow	Seasonal Streamflow amount (in snowmelt season)	Cumulative run-off on July 1 and August 1	Annual water supply planning for the year done based on July 1 or August 1 reservoir level estimates (depending on the reservoir).
Floods	Streamflow	Seasonal Streamflow amount (in snowmelt season)	% of average annual inflow for Apr-July	Reservoir management. This metric is an input into some reservoir operations models.
Water Supply	Streamflow	Inter-annual variability in summer streamflow	10th, 50th and 90th percentile volumes of Apr-May-June-July sum, over several years	Understanding range of possibilities while planning for water supply on timescales of 1 or more years.
Water Supply	Streamflow	Low-end Streamflow	7-day 10 year low flows	Water quality management (issuing discharge permits), and water supply planning during dry years (determining permit limits for water withdrawals).

Water Supply	Streamflow	Low-end Streamflow	Bottom 10th or 25th percentile volumes of streamflow (especially in dry years)	Water supply planning during dry years (or droughts).
Water Supply	Streamflow	Streamflow Timing	Center of mass	Water supply planning for time-sensitive uses (crops, timed water diversions, water in ecosystems), and reservoir operations management.
Water Supply	Streamflow	Streamflow Timing	Quartiles: Day on which 25%, 50%, and 75% flow (beginning at start of water year) has passed	Water supply planning for time-sensitive uses (crops, timed water diversions, water ecosystems), and reservoir operations management.
Floods	Streamflow	Peakflow	Intensity Duration and Frequency curves for different flow events	Storm water management & design, and flood protection.
Floods	Streamflow	Variability of Streamflow	Probabilities of exceedance for certain run-off thresholds (ASPE design thresholds, which vary by region and infrastructure type)	Storm water management & design, and flood protection.
Water Supply	Snowpack	Seasonal snowpack volume	Monthly snow water equivalent: Total Water availability metric on a monthly scale. (especially Dec-Jul)	Understanding streamflow characteristics and the state of the water system - and its potential to meet demands. E.g. Winter months SWE (Dec-Jan-Feb) is used in seasonal forecasting of reservoir levels on July 1.

Water Supply	Snowpack	Seasonal snowpack volume	% of annual snowpack accumulated in different months	Seasonal reservoir in-flow forecasting, and understanding expectations with regard to early versus late season snow accumulation.
Water Supply	Snowpack	Annual cycle of snow accumulation and melt	SWE triangle(Rhoades et al., 2018) - Peak snow (amount and timing), and its relationship with average snow-accumulation and -melt rates, and timing and length of accumulation and melt seasons	On-stream reservoir management, and to understand future streamflow characteristics. Shape of the triangle helps better understand the changing dynamics of the snow season, and what to expect in terms of runoff timing and amounts.
Water Supply	Snowpack	Inter-annual Variability in Snowpack	Deviations from historical mean in monthly SWE	Water supply planning, especially for supply restrictions.
Water Supply	Snowpack	Inter-annual Variability in Snowpack	Upper and lower end of distribution: 10^{th} and 90^{th} percentile of annual snowpack for wet and dry years (or top and bottom 25 pc)	Water supply planning, especially for supply restrictions.
Water Supply	Droughts/Dry Spells	Low precipitation	Standardized Precipitation Index (SPI): Number of dry or wet years	Drought planning, and understanding dry spells.
Water Supply	Droughts/Dry Spell	Net water availability	SPEI (Standardised Precipitation-Evapotranspiration Index)	Drought planning, and understanding dry spells.
FLORIDA				
Issue	**Hydroclimatic Phenomenon**	**Aspect of Phenomenon**	**Decision-relevant Metric**	**Decision/Use**

Floods	Streamflow	Peakflow	Multi-year probability distribution of instantaneous maximum flow on an annual scale. i.e. Annual Maxima	Flood management and planning.
Floods	Streamflow	Peakflow	Timing of annual maxima	Flood management and planning.
Floods	Streamflow	Peakflow	5-year 1-hour volume 5-year 1-day volume 10-year 3-day volume 25-year 3-day volume 100-year 3-day volume	Stormwater infrastructure design criteria (for different infrastructure), and flood management, especially planning water storage facilities.
Water Supply	Streamflow	Low-end Streamflow	7-day 10 year low flow (7Q10)	Water supply planning, especially water quality for dry years, and drought planning.
Water Supply	Streamflow	Low-end Streamflow	Flow anomalies at monthly timescales	Water supply planning to calculate potential water shortages, and drought monitoring.
Water Supply	Streamflow	Annual/Monthly flow	Average Monthly or Annual Flow volumes	Water supply planning for restoration activities.
Water Supply	Streamflow	Monthly flow	Percentage of annual flow occurring in each month	Water supply planning for restoration activities, and reservoir operations management such as managing reservoir use-re-fill cycle.
Water Supply	Streamflow	Variability of Streamflow	Standard deviation of monthly or annual flow volumes	Planning for variability in water supply and for restoration activities.

Water Supply	Streamflow	Peakflow	Daily max flow	Water quality management, e.g. planning water source rotations.
Floods	Rainfall	Extreme Rainfall	Intensity Duration Frequency or IDF curves, specifically, 1-day, 3-day and up to 7-day rainfall events, for 10, 25, 50 and 100 year frequency intervals.	To calculate applicable discharge rates for different storm water management infrastructure. Design criteria used for drainage and flood protection are in terms of IDFs. In other words, designing of standard engineering practices for infrastructure.
Floods	Rainfall	Extreme Rainfall	Change in temporal frequency of historic storms of particular return frequencies (10-100 yrs)	To understand how design storm criteria for different infrastructure may change in the future (roads 10 yrs, houses 100 yrs,), and for recurrent/nuisance flooding monitoring.
Floods	Rainfall	Extreme Rainfall	Frequency and duration of rainfall events greater than 3 or 5 inches in summer season (July, August, September)	For water supply preparedness, to understand cumulative water availability in key supply months.
Floods	Rainfall	Extreme Rainfall	Probable maximum precipitation**.** For 1-day, 3-day and maybe up to 7-day events	Large storage infrastructure design (like high dams).
Water Supply	Rainfall	Annual Rainfall	Total annual rainfall volumes	Water supply planning, and drought monitoring.
Water Supply	Rainfall	Monthly Rainfall	Monthly rainfall distributions	Water supply planning, and drought monitoring.
Water Supply	Rainfall	Variability in Rainfall	Rainfall anomalies at Monthly time scales	Water supply planning, and drought monitoring.

Water Supply	Rainfall	Extreme Rainfall	Rainfall Geometric curve (analogous to the SWE triangle). Including start of wet season, duration of wet season, peak volume and other related parameters	Understanding how the annual water season would change in the future.
Water Supply	Droughts/Dry Spells	Drought metrics	Frequency of 1-, 2-, 3-year duration droughts.	Drought prediction and management, and planning future water infrastructure investments.
Water Supply	Droughts/Dry Spells	Drought metrics	Change in temporal frequency of historic multi-year droughts of a particular return period (e.g. 1 in 10 year droughts)	Drought prediction and management, and planning future water infrastructure investments.
Water Supply	Droughts/Dry Spells	Low Rainfall	Probability distribution of annual rainfall totals: particularly focusing on low end of that distribution and how often that occurs	Water supply planning, drought monitoring, and planning future water infrastructure investments.
Water Supply	Droughts/Dry Spells	Demand-Supply gap in Streamflow	Streamflow curves showing the general shape and timing of runoff supply and water demand, and the differential (or gap) between the two	Water supply planning to calculate potential water shortages, and water conservation measures (reduction targets), drought monitoring, and planning future water infrastructure investments.
SUSQUEHANNA				
Issue	**Hydroclimatic Phenomenon**	**Aspect of Phenomenon**	**Decision-relevant Metric**	**Decision/Use**

Water Supply	Streamflow	Peakflow	Flows that exceed 250,000 cfs or 400,000 cfs scour threshold for Conowingo Reservoir	Water quality management, specifically sediment and nutrient management for lower Susquehanna River and Chesapeake Bay.
Water Supply	Streamflow	Peakflow	10- year frequency 3-year duration high flows for Oct-March	Water quality management in terms of monitoring Chesapeake Bay water quality standards.
Floods	Streamflow	Peakflow	Probable Maximum Flood as defined by NOAA.	Dam safety and flood risk management considerations.
Water Supply	Streamflow	Low-end Streamflow	7-day10-year low flow	Water quality management in terms of wastewater assimilation standards for discharge permits, and water supply planning in terms of passby flows or conservation releases for water withdrawal permits.
Water Supply and Droughts	Streamflow	Low-end Streamflow	Monthly 95th percent exceedance (P95), as well as P90, P85, P80, and P75 flows, i.e. Px flow is the flow magnitude that is exceeded x% of the time.	Water supply monitoring for passby flows, conservation releases, and low flow augmentation associated with water use permits. Drought conditions monitoring and issuing drought watch, warning, and emergency declarations

Water Supply	Streamflow	Average/ cumulative flows	Mean annual flow and harmonic mean flow	Water supply planning, for monitoring passby flows and conservation releases associated with water withdrawal permits. Water quality management for calculating design flows for effluent limitations based on water quality criteria.
Water Supply and Drought s	Streamflow	Low-end Streamflow	July through November, monthly average and P95 flows.	Water supply planning, P95 flows are a trigger for consumptive use mitigation operations.
Water Supply	Streamflow	Monthly Streamflow	Percentage of annual streamflow occurring in each month	Water supply planning considering use and availability including monthly variable demands and in-stream flow needs.
Water Supply	Streamflow	Variability of Streamflow	Standard deviation of monthly or annual flows	Water supply planning considering use and availability including monthly variable demands and in-stream flow needs.
Floods	Rainfall	Extreme Rainfall	IDF curves, (Generic 1-day, 2-day, 3-day up to 7-day duration, 2-year, 5-year, 10-year up to 100-year storms)	Flood risk management, and stormwater management and design criteria, including roadway drainage.
Water Supply and Drought s	Rainfall	Cumulative rainfall	30-,60-,90-,120-day cumulative rainfall	Drought monitoring and declarations.
Water Supply and Floods	Rainfall	Annual cycle of Rainfall	Rainfall geometry, Focusing on wet and dry seasons	Flood risk management, and water supply planning.

Water Supply and Floods	Snowpack	Annual cycle of snow accumulation and melt	SWE triangle, Focusing on peak date, accumulation rate, % of snow accumulation in different months of snow season	Water supply planning in terms of use and availability, flood control reservoir operations, and for calibration of hydrologic models.
Water Supply	Snowpack	Monthly snowpack	Monthly water availability from snow	Water supply planning in terms of use and availability, and for calibration of hydrologic models.
Floods	Snowmelt	Peak flow / pulse events	Frequency of Rain-on-snow events and magnitude of associated run-off	Flood control reservoir operations.
Water Supply	Dry spells	Low precipitation	Precipitation anomalies i.e.. Rolling 90-day mean precipitation and its departures from normal.	Drought monitoring - Precipitation deficit informs drought status.
Water Supply	Dry spells	Evapotranspirati on (ET)	June July August evapotranspiration (or broadly May-Sept ET)	Consumptive use and water demand evaluation.

Table B. 1: Full list of decision-relevant metrics. The table highlights the full list of the key issues, hydroclimatic phenomena, aspect of phenomena and decision-relevant metrics for each region. The last column also describes some of the potential decisions or uses for these metrics that were highlighted by the case study water managers.

APPENDIX C: FOR CHAPTER 3

Figure C.1: Trigonometric approach for converting daily to hourly temperature

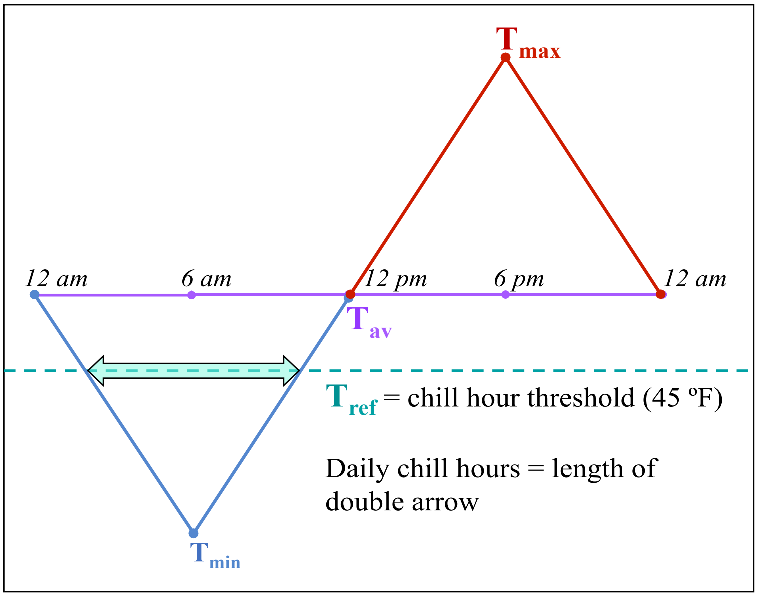

Figure C. 1: Computation of daily chill hours from daily $\boldsymbol{T_{av}}$ and $\boldsymbol{T_{min}}$ using the trigonometric approximation method. Here, T_{av} is defined as the average of T_{min} and T_{max}. The length of the double arrow represents the magnitude of daily chill hours. Figure adapted from Baldocchi & Wong, 2007.

Equation. C.1: Calculating daily chill hours

$$\mathrm{Ch(d)} = \frac{12 * \left(45 - \mathrm{T_{min}(d)}\right)}{\mathrm{T_{av}(d)} - \mathrm{T_{min}(d)}}$$

Equation. C 1: Equation for calculating daily chill hours from daily average and minimum temperature

Where:

$\mathrm{Ch(d)}$	Chill hours in a day
(d)	Daily
$T_{av}\ (d)$	Average surface temperature for the day
$T_{min}\ (d)$	Minimum surface temperature for the day

Table C.1: List of the LOCA GCMs

#	Model name	Ensemble run	#	Model name	Ensemble run
1	ACCESS1-0	'r1i1p1'	**17**	GFDL-ESM2M	'r1i1p1'
2	ACCESS1-3	'r1i1p1'	**18**	GISS-E2-H	'r2i1p1'
3	bcc-csm1-1	'r1i1p1'	**19**	GISS-E2-R	'r2i1p1'
4	bcc-csm1-1-m	'r1i1p1'	**20**	HadGEM2-AO	'r1i1p1'
5	CanESM2	'r1i1p1'	**21**	HadGEM2-CC	'r1i1p1'
6	CCSM4	'r6i1p1'	**22**	HadGEM2-ES	'r1i1p1'
7	CESM1-BGC	'r1i1p1'	**23**	inmcm4	'r1i1p1'
8	CESM1-CAM5	'r1i1p1'	**24**	IPSL-CM5A-LR	'r1i1p1'
9	CMCC-CM	'r1i1p1'	**25**	IPSL-CM5A-MR	'r1i1p1'
10	CMCC-CMS	'r1i1p1'	**26**	MIROC5	'r1i1p1'
11	CNRM-CM5	'r1i1p1'	**27**	MIROC-ESM	'r1i1p1'
12	CSIRO-Mk3-6-0	'r1i1p1'	**28**	MIROC-ESM-CHEM	'r1i1p1'
13	EC-EARTH	'r2i1p1'	**29**	MPI-ESM-LR	'r1i1p1'
14	FGOALS-g2	'r1i1p1'	**30**	MPI-ESM-MR	'r1i1p1'
15	GFDL-CM3	'r1i1p1'	**31**	MRI-CGCM3	'r1i1p1'
16	GFDL-ESM2G	'r1i1p1'	**32**	NorESM1-M	'r1i1p1'

Table C. 1: List of 32 GCMs and respective ensemble members, for which LOCA data was analyzed.

Table C.2: List of the raw GCMs

#	Model name	Ensemble run	#	Model name	Ensemble run
1	ACCESS1-0	r1i1p1	**30**	EC-EARTH	r8i1p1
2	ACCESS1-3	r1i1p1	**31**	EC-EARTH	r9i1p1
3	BNU-ESM	r1i1p1	**32**	EC-EARTH	r12i1p1
4	bcc-csm1-1	r1i1p1	**33**	GFDL-CM3	r1i1p1
5	CanESM2	r1i1p1	**34**	HadGEM2-AO	r1i1p1
6	CanESM2	r2i1p1	**35**	HadGEM2-CC	r1i1p1
7	CanESM2	r3i1p1	**36**	HadGEM2-ES	r1i1p1
8	CanESM2	r4i1p1	**37**	HadGEM2-ES	r2i1p1
9	CanESM2	r5i1p1	**38**	HadGEM2-ES	r3i1p1
10	CCSM4	r1i1p1	**39**	HadGEM2-ES	r4i1p1
11	CCSM4	r2i1p1	**40**	inmcm4	r1i1p1
12	CCSM4	r6i1p1	**41**	IPSL-CM5A-LR	r1i1p1
13	CESM1-BGC	r1i1p1	**42**	IPSL-CM5A-LR	r2i1p1
14	CESM1-CAM5	r1i1p1	**43**	IPSL-CM5A-LR	r3i1p1
15	CMCC-CESM	r1i1p1	**44**	IPSL-CM5A-LR	r4i1p1
16	CMCC-CM	r1i1p1	**45**	IPSL-CM5A-MR	r1i1p1
17	CMCC-CMS	r1i1p1	**46**	IPSL-CM5B-LR	r1i1p1
18	CNRM-CM5	r1i1p1	**47**	MIROC-ESM-CHEM	r1i1p1
19	CSIRO-Mk3-6-0	r1i1p1	**48**	MIROC-ESM	r1i1p1
20	CSIRO-Mk3-6-0	r2i1p1	**49**	MIROC5	r1i1p1
21	CSIRO-Mk3-6-0	r3i1p1	**50**	MIROC5	r2i1p1
22	CSIRO-Mk3-6-0	r4i1p1	**51**	MIROC5	r3i1p1
23	CSIRO-Mk3-6-0	r5i1p1	**52**	MPI-ESM-LR	r1i1p1
24	CSIRO-Mk3-6-0	r6i1p1	**53**	MPI-ESM-LR	r2i1p1
25	CSIRO-Mk3-6-0	r7i1p1	**54**	MPI-ESM-LR	r3i1p1
26	CSIRO-Mk3-6-0	r8i1p1	**55**	MPI-ESM-MR	r1i1p1
27	CSIRO-Mk3-6-0	r9i1p1	**56**	MRI-CGCM3	r1i1p1
28	CSIRO-Mk3-6-0	r10i1p1	**57**	NorESM1-M	r1i1p1
29	EC-EARTH	r2i1p1			

Table C. 2: List of 29 GCMs and respective ensemble members, for which raw data was analyzed.

Equation. C.2: Equation for bias correction

$$CF_{Tav,m} = \mu_m\left(T_{av,obs,hist}(d)\right) - \mu_m\left(T_{av,mod,hist}(d)\right)$$

$$CF_{Tmin,m} = \mu_m\left(T_{min,obs,hist}(d)\right) - \mu_m\left(T_{min,mod,hist}(d)\right)$$

Equation. C 2: Equation for calculating monthly correction values for each of the model runs from observed and modeled $\boldsymbol{T_{av}}$ and $\boldsymbol{T_{min}}$. These monthly correction factors were added to daily $\boldsymbol{T_{av}}$ and $\boldsymbol{T_{min}}$ values to get corresponding bias-corrected daily temperature values. The same correction factors were used for adjusting both historical and future temperatures.

Where:

$CF_{Tav,m}$	Correction factor for average temperature for month m
$CF_{Tmin,m}$	Correction factor for minimum temperature for month m
μ_m	Mean for a particular month (m)
$hist$	Historical time period 1971-2012
(d)	Daily
obs	Observed values
mod	Modeled values
T_{av}	Average surface temperature
$\mu_m\left(T_{av,obs,hist}(d)\right)$	Mean of all observed daily T_{av} for month m, for the period 1971-2012
$\mu_m\left(T_{av,mod,hist}(d)\right)$	Mean of all modeled daily T_{av} for month m, for the period 1971-2012
T_{min}	Minimum surface temperature
$\mu_m\left(T_{min,obs,hist}(d)\right)$	Mean of all observed daily T_{min} for month m, for the period 1971-2012
$\mu_m\left(T_{min,mod,hist}(d)\right)$	Mean of all modeled daily T_{min} for month m, for the period 1971-2012

Figure C.2: Historical and future projections of mean annual chill hours for different time periods

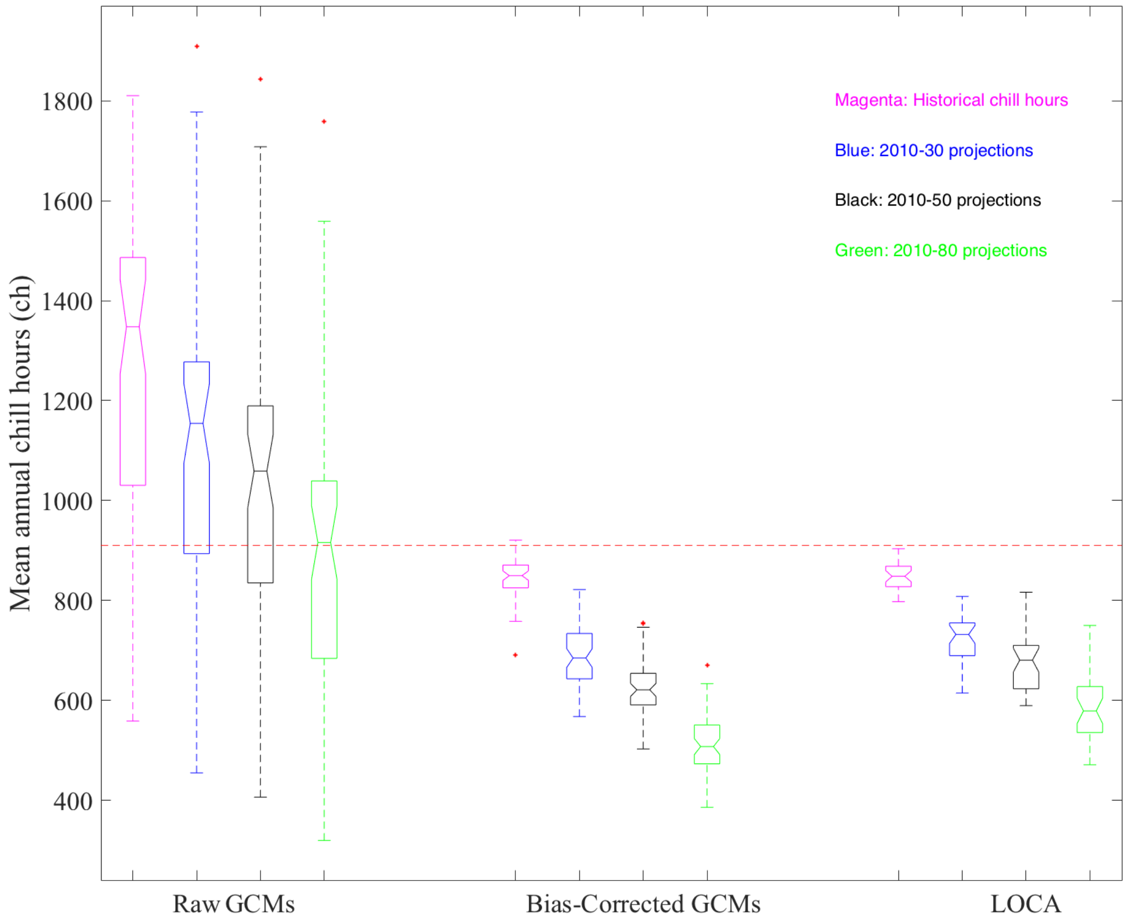

Figure C. 2: Mean annual chill hour projections from raw GCM, bias corrected GCM and LOCA datasets (for historical and different future time periods). The box and whisker plots show the combined modeled results from all GCMs. The notch within each box represents the median results from all GCM simulations: values in the box above the median are the top 50% results, and the whisker above the median is the top 25%. The graph shows that both the LOCA data and our simple linear bias correction correct the cold bias in raw GCM results, and this correction is carried over into the future. The correction also reduces the inter-model variability in mean chill results. The red dashed line represents observed mean chill hours from 1971-2012.

Figure C.3: Historical and future projections of chill hours slope for different time periods

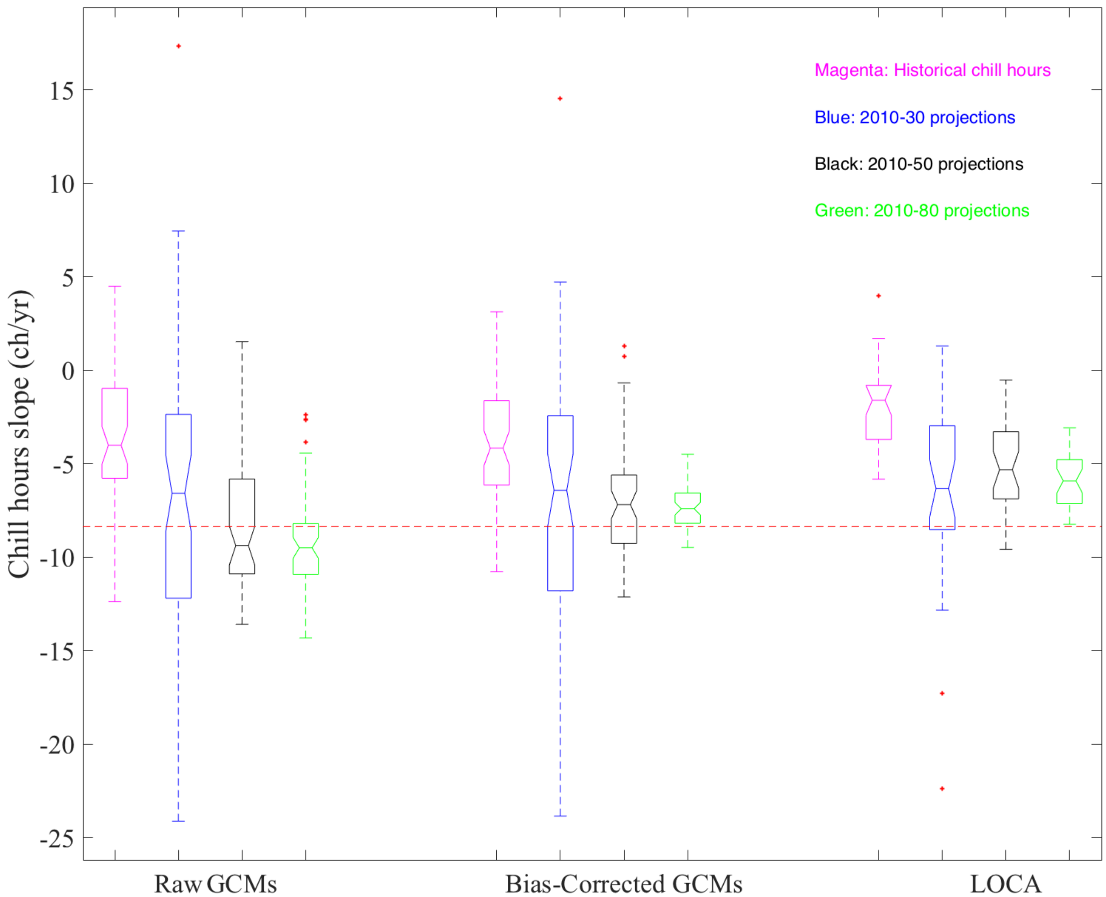

Figure C. 3: Chill hours slope projections from raw GCM, bias corrected GCM, and LOCA datasets (for historical and different future time periods). The box and whisker plots show the combined modeled results from all GCMs. The notch within each box represents the median results from all GCM simulations: values in the box above the median are the top 50% results, the whisker above the median is the top 25%, while the outliers are marked as red plus signs. The graph shows that, particularly for the future time periods, the decreasing trend in chill hour slope projections reduces in magnitude with bias correction. The red dashed line represents observed chill hours slope from 1971-2012.

Figure C.4: Non-linearity of the chill metric

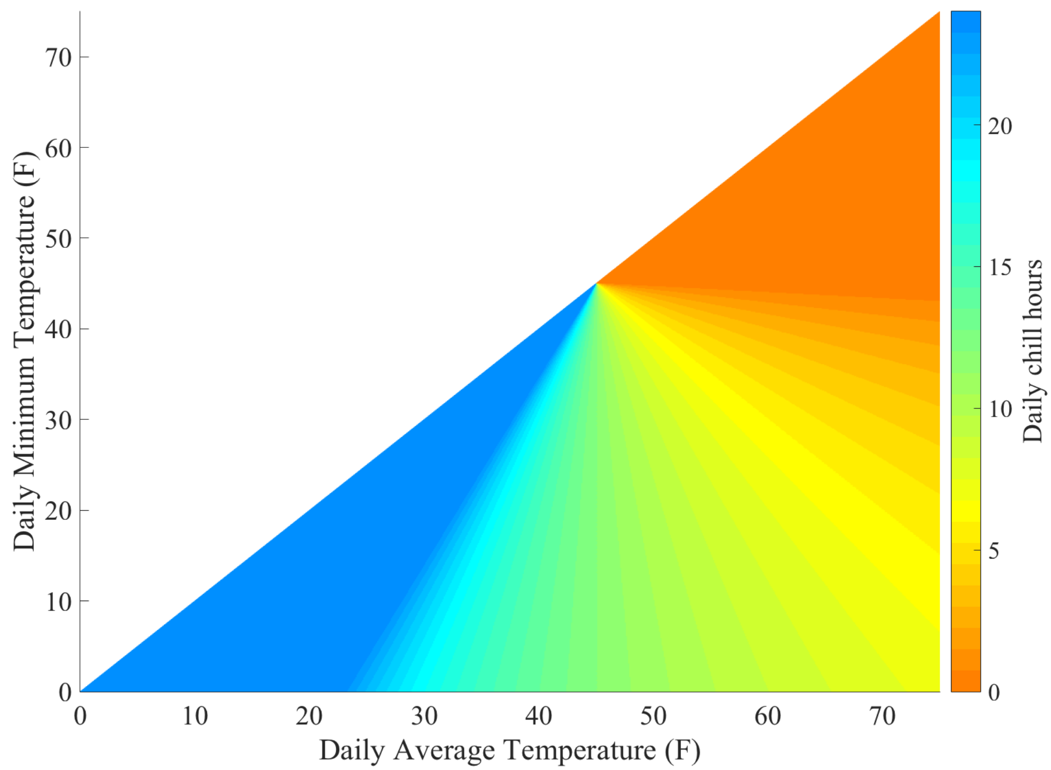

Figure C. 4: Two-dimensional plots of daily chill hours as a function of daily T_{min} and T_{av} over a range of values. It shows that various combinations of $T_{min}$and T_{av} can give the same magnitude of chill hours and that the sensitivity of chill hours to small perturbations in $T_{min}$and T_{av} can be highly variable across the range of potential values. Chill hours can be highly sensitive to incremental temperature changes when $T_{min}$and T_{av} are close to the 45°F threshold value, but relatively insensitive when either both values are low (solid blue area to lower left) or both values are high (solid red area to upper right). It follows that the same incremental change in either T_{min} or T_{av} can have a relatively large or small impact on chill hours depending on the initial starting point for these values.

Figure C.5: Chill hours in 2050 for different model samplings (full-scale figure)

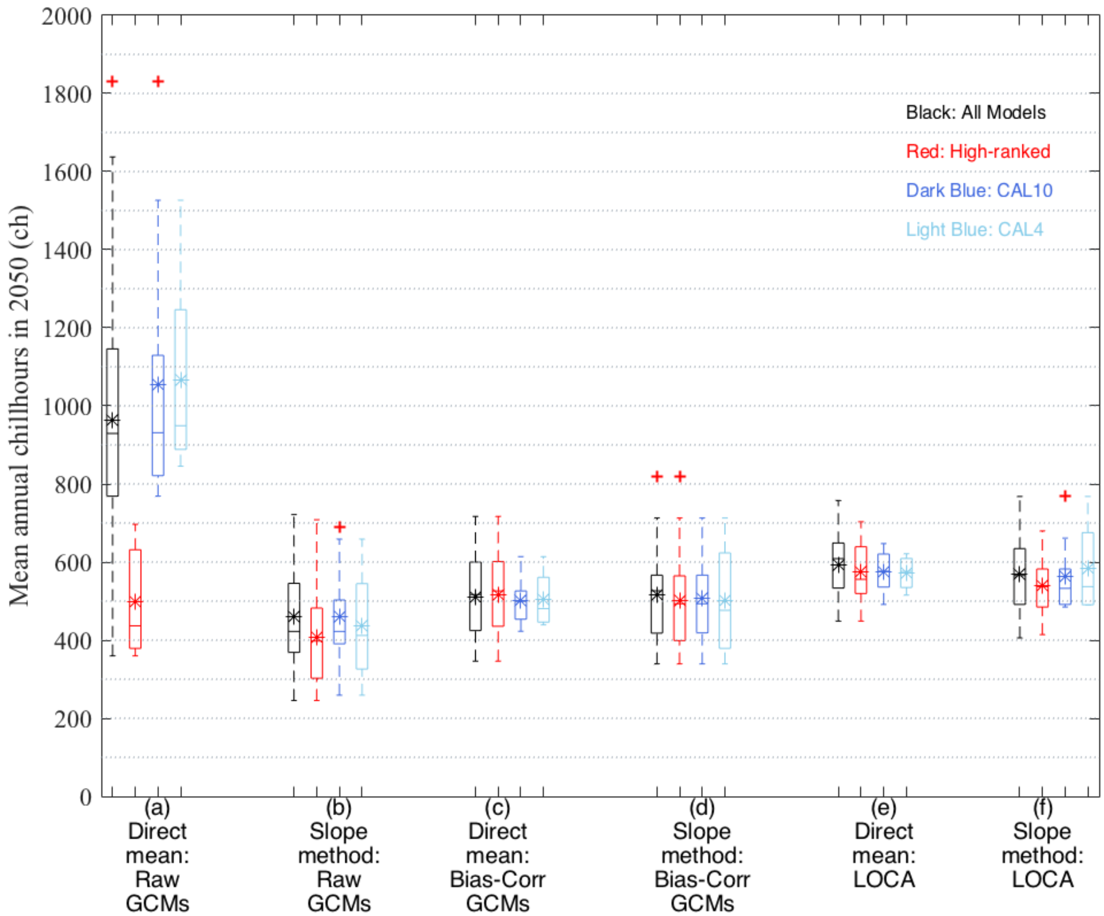

Figure C. 5: 2050 chill hours computed using different climate datasets, GCM samplings, and computation methods. Each cluster of box plots represents 2050 chill hours computed through one method (Direct mean OR Slope Method), and for one dataset (raw GCM, Simple bias-corrected GCM or LOCA). The asterisks show the mean values, and the red plus signs represent the outliers. The dotted light grey lines have been plotted for easy comparison of the mean and median values of the different choices. This is the full-scale graph of Figure 6 in the main text.

Figure C.6: Comparison between raw GCMs and LOCA predictions of trends in winter season (Nov-Dec-Jan-Feb) $\boldsymbol{T_{min}}$ and $\mathbf{T_{av}}$

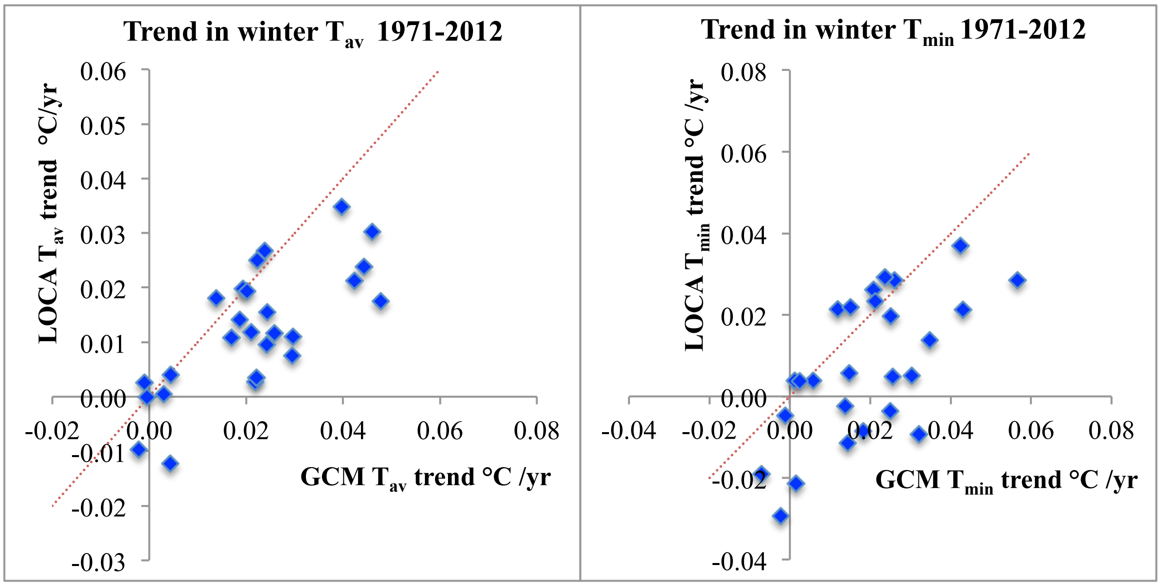

Figure C. 6: Pair-wise comparison between temperature trend predictions from raw GCMs (X-axis), and from LOCA (Y-axis) illustrating pre- and post- downscaling trends for the same model runs. Each of the blue diamond markers represent trend predictions from a single GCM run pre- and post- LOCA downscaling. Temperature trends were calculated as the slope of the average or minimum temperatures for the winter season (mean of Nov-Dec-Jan-Feb temperatures) over the period from 1971 to 2012. The red dotted line is presented as a reference linear line. The figure shows that the magnitude of the warming trend in T_{av} and T_{min} of the raw GCMs is systematically higher than the LOCA (i.e. more points are further to the bottom of the linear line than the top). For reference, the observed T_{av} trend for the Fresno weather station is 0.029 °C /yr and T_{min} trend if 0.034 °C /yr.

APPENDIX D: FOR CHAPTER 4

Detailed methodology used for reviewing co-production projects

We first collected all literature published 2016 to early 2019 that included climate change adaptation (or climate change resilience) and co-production (and variants) in the title, abstract, or keywords. We then screened the abstracts of these results to eliminate all papers except for those that claimed to apply techniques of co-production. This process eliminated theoretical and review papers, papers which discuss co-production but don't claim to apply it, extraneous uses of the term co-production (e.g., related to energy production), and papers that were not primary accounts of a project (i.e. where the authors were not directly involved in at least one aspect of the co-production exercise itself). This screening process resulted in 21 peer-reviewed papers, which were systematically read by at least two authors per paper. Although each of these papers contain results that extend beyond the focus of our study, we restricted our review to only those components of the papers that reported on the specific aspects of the co-production projects. While we acknowledge that the universe of burgeoning co-production activities extends beyond peer-reviewed papers (i.e. grey literature or granting reports), we are confident this represents most of the recent peer-reviewed, project-scale literature that explicitly refers to their work as co-production in the context of climate change adaptation.

The final list of 21 papers has been provided in the Table below. Many of these projects aimed at improving the understanding of regional climate and its local impacts, assessing adaptation options, and exploring factors impacting adaptation. Several others involved developing adaptation plans and actions, and improving adaptive capacity. For each of these projects we examined the following four characteristics:

- the main <u>intent</u> or aim of the co-production projects,
- the <u>engagement approaches</u> used for practicing co-production,
- the types of <u>outputs</u> and <u>outcomes</u> that are reported and
- whether and how are projects are being <u>evaluated</u>.

We also looked at the following secondary questions and embed these into our findings:

- What was the <u>aim</u> of the project?
- Who were the <u>participants</u> in the co-production?
- In summary, what <u>benefits</u> are attributed to co-production and what <u>challenges</u> does it face?

Finally, we conducted a descriptive synthesis of the project information to generate broad themes and comparisons between and among the projects.

List of the 21 papers reviewed

Authors	Date	Title
Wallis et al.	2017	Charting the emergence of a ‘knowing system’ for climate change adaptation in Australian regional natural resource management
Jacobs et al.	2018	Towards a climate change adaptation strategy for national parks: Adaptive management pathways under dynamic risk
Ruiu et al.	2017	Re-staging La Rasgioni: Lessons learned from transforming a traditional form of conflict resolution to engage stakeholders in agricultural water governance
Vedeld et al.	2016	Climate adaptation at what scale? Multi-level governance, resilience, and coproduction in Saint Louis, Senegal
Lavrillier and Gabyshev	2018	An emic science of climate. Reindeer Evenki environmental knowledge and the notion of an “extreme process”
Borquez et al.	2018	Resilience to climate change: from theory to practice through co-production of knowledge in Chile
Aldunce et al.	2016	Unpacking resilience for adaptation: Incorporating practitioners' experiences through a transdisciplinary approach to the case of drought in Chile
Devisscher et al.	2016	Understanding the socio-institutional context to support adaptation for future water security in forest landscapes
Bezner Kerr et al.	2018	Knowledge politics in participatory climate change adaptation research on agroecology in Malawi
Bremer et al.	2017	Narrative as a method for eliciting tacit knowledge of climate variability in Bangladesh
Turner et al.	2016	Lessons from the construction of a climate change adaptation plan: A Broads wetland case study
Scott et al.	2018	The story of water in windhoek: A narrative approach to interpreting a transdisciplinary process
Kench et al.	2018	Co-creating Resilience Solutions to Coastal Hazards Through an Interdisciplinary Research Project in New Zealand
Bhave et al.	2018	Water Resource Planning Under Future Climate and Socioeconomic Uncertainty in the Cauvery River Basin in Karnataka, India
Laursen et al.	2018	Collaboration Across Worldviews: Managers and Scientists on Hawai‘i Island Utilize Knowledge Coproduction to Facilitate Climate Change Adaptation

Miller et al.	2017	Co-producing simulation models to inform resource Management: A case study from southwest South Dakota
Lorencova et al.	2018	Participatory climate change impact assessment in three Czech cities: The case of heatwaves
Laudien et al.	2018	The Dutch adaptation web portal: seven lessons learnt from a co-production point of view
Pons et al.	2017	On the Production of Climate Information in the High Mountain Forests of Guatemala
Visconti	2017	Community-based adaptation measures for Water Sensitive Urban Design in context of socio-environmental vulnerability
Fresco and Timm	2016	Fostering resilience in the face of an uncertain future: Using scenario planning to communicate climate change risks and collaboratively develop adaptation strategies

Outputs

As we inquire the extent to which co-production is truly as generative an activity as the name implies, we seek to understand what, in the most tangible and immediate terms, is produced during co-production. We observe that six main types of outputs (Figure D. 1) are produced through efforts that aim to co-produce. The first is publications, which by default includes the peer-reviewed article published and assessed in this study. In addition, these projects also produced various types of referenced documents such as climate impact assessment reports, adaptation needs assessment reports, workshop reports, scoping documents, and other similar reporting outputs. A second slightly different type of output included outreach or communication material, which included communication briefs, informational flyers, communication strategies, etc. Some projects report a third type of output which is the development of new data or concepts, such as results from citizen science or collaboratively collected climatological data, or new conceptual understandings of climate/adaptation emerging from collaborative efforts. The fourth type of output is broadly classified as models and decision-support tools, which may include climate or impact models of varying complexity, scenarios of adaptation (sometimes formally integrated into modeling), and other diagnostic and planning tools. Strategies comprise the fifth output category and encompass the sets of recommendations, pathways, plans, and adaptive response strategies that were developed as part of the co-production efforts. One project also reported undertaking some direct adaptation interventions which forms a sixth type of output from co-production wherein the project undertook pilot projects to implement adaptive farming strategies. And finally, the seventh type of output, not surprisingly, is the many forms of activities undertaken by projects. These include workshops, educational activities, and other engagement practices that in the process of characterizing co-production become considered as focal outputs of the process.

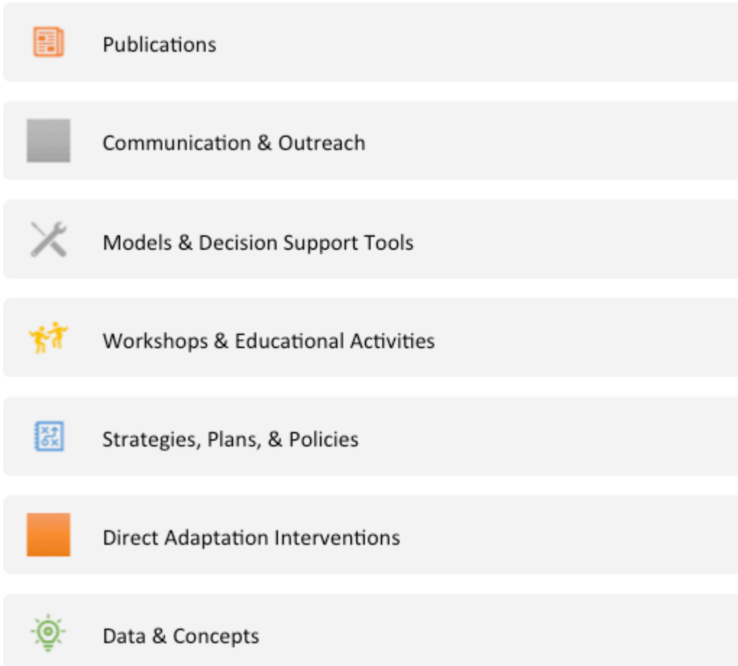

Figure D. 1: Types of outputs reported by co-production projects