Forecasting climate change impacts on watershed-based ecosystem services in Hawaii: A participatory modeling approach
Introduction

The local-scale ecological impacts of global climate change are highly uncertain (Denman et al. 2007; Friedlingstein et al. 2006; Visser et al. 2000). Even though it is widely acknowledged that the impacts of these changes will be felt on the local level, modeling frameworks that translate these global changes in terms relevant to small-scale ecological decision-makers and natural resource managers remain somewhat elusive given the difficulties in down-scaling and coupling highly complex global processes with highly complex local processes (Denman et al. 2007; Friedlingstein et al. 2006; Sitch et al. 2008). The inability of current modeling methods to make climate change scenarios relevant at the local ecological scale emerges from a general lack of methods that allow resource managers to capture and link these global processes with local-scale dynamics that define the locally relevant connections between climate change, ecological dynamics and natural resource management priorities. Understanding relevant local scale dynamics and providing a way for local decision-makers to anticipate climate change impacts in terms relevant to their management priorities is therefore key if communities are expected to learn about and collectively adapt to undesired outcomes (Pahl-Wastl and Hare 2004).

Problem and Research Objectives

Climate change in the Pacific Islands provide an ideal context to test ideas regarding the integrating of climate change scenarios, environmental data and expert-based model to understand and predict impacts. Climate change and its macro-effects on temperature, rainfall, sea level, and extreme events are likely to bring about localized changes in the coastal zone, agricultural systems, human settlements and infrastructure, water resources, human health, and macroeconomic performance in Pacific Island countries (Barnett 2005; Carter et al. 2001; Easterling et al. 2007). However, local-scale ecological dynamic changes brought about by changes in global carbon cycling are currently poorly understood (Denman et al. 2007; Friedlingstein et al. 2006; Sitch et al. 2008) although some general trends have recently emerged (Rosenzweig et al. 2007). For example, recent studies suggest that there will be less frequent but higher intensity rainfall patterns across the Pacific Islands due to climate change. Decreases in precipitation and base flow (Chu et al. 2010; Oki 2004), the continuation of these decreasing trends may impact freshwater ecosystems and aquatic species. Decrease in streamflow (Bassiouni and Oki 2012; Oki 2004) may also interrupt movement of native species along streams and may prevent species that spend their larval stages in the ocean from returning to the streams to complete their life cycle (Keener et al. 2012). Invasive plant and animal species are established and expanding in many forests and their responses to climate change will interact with those of native species to determine future ecosystem composition and processes. Native species have to compete with alien species for food and shelter. Existing climate zones are projected to shift, generally upslope, with some eventually disappearing (Benning et al. 2002). The ability of native plant species to adapt to these changes will be affected by competition with aggressive invasion. Available habitat decreases rapidly with elevation, putting species currently found on upper slopes and ridges at special risk (Eiben and Rubinoff 2010; Keener et al. 2012). Currently, native species in their most pristine conditions are located in these regions with high elevation. Spread of invasive species to these regions is a foreseeable risk caused by climate change.
Although researchers are beginning to synthesize the ecological impacts of these effects cumulatively (Price et al. 2009), information about how habitat managers can mitigate these unwanted outcomes is generally not available. Indeed, climate change has already affected Hawaii by increasing air and sea-surface temperatures that exceed the global average (Giambelluca et al. 2008) and a 10% reduction in streamflow over the last 30 years (Oki 2004). General circulation model projections indicate that continued warming and drying will be paired with more intense, yet less frequent, rainfall events (Chu and Chen 2005; Chu et al. 2010; Norton et al. 2011) and stream flow in some Hawaiian watersheds will continue to be reduced by 6.7% up to 17.2% over the next 40 years (Safeeq and Fares 2011). In addition, erosion regimes and changes in nutrient loading are expected to accompany changes in water availability (Furniss et al. 2010). All of these hydrological and ecological changes to Hawaii’s watersheds are thought to be accompanied by decreases in habitat suitability for native species (Keener et al. 2012). However, methods to forecast future changes in terms useful for wildlife management are highly underdeveloped and poorly understood, especially on island communities that are predicted to be disproportionally affected by climate change (Barnett 2005). Insufficient and uncertain comprehension of climate change induced outcomes is thought to limit social adaptation responses (Pahl-Wastl and Hare 2004). Therefore, unique island hydrogeology and climate, together with ambiguous climate change prediction, will add uncertainties and complications to climate change management planning. While it is unknown how watershed and habitat decision-making in the future will be affected by climate changes, poorly-informed decision-making and failure to reduce uncertainty associated with these changes will likely increase the social and ecological costs of climate change on island communities.

Given the difficulties in understanding how water quality and quantity changes will impact habitat, we present a modeling approach intended to provide decision-support by coupling watershed data generated through common models with a relatively novel method of pooling expert knowledge to predict how watershed changes will impact life history functions of managed bird species, mediated by understanding changes in habitat dynamics. To demonstrate the usefulness of this approach to understanding complex habitat changes based on climate change projections, in this paper, we use case study data collected from three endangered water birds (Hawaiian Stilt, Coot, and Moorhen) on the Hawaiian Island of Kauai.

**Methodology**

The modeling framework includes integrating two models in a five-stage process: (1) defining climate change scenarios, (2) modeling watershed changes under climate change scenarios using AnnAGNPS, (3) describing relationships between watershed dynamics and bird habitat using expert-based modeling using Fuzzy-logic Cognitive Mapping (FCM), (4) developing model scenarios by integrating the two models, and (5) using scenario results to discuss adaptation and management strategies.
Climate Change Scenarios

To define climate change reference scenarios we use data from the IPCC report that includes different CO\textsubscript{2} emission rates and their effect on temperature and precipitation changes for the next 100 years. Four CO\textsubscript{2} emission rates (330 ppm [2003–2004 rate], 550 ppm, 710 ppm, and 970 ppm) were used for developing model scenarios. In addition, precipitation changes (±5%, ±10%, and ±20%) specific to the Hawaiian Islands were also used for scenarios based on previous work (Safeeq and Fares 2011). The model simulations were based on the IPCC’s extreme temperature values of the “likely” range (1.1°C and 6.4°C). Safeeq and Fares (2011) previously developed 24 scenarios in the Pacific Islands using these three components (CO\textsubscript{2} emission rates, temperature, and precipitation variations), however, only six climate change scenarios (extreme as well as intermediate scenarios) out of these twenty-four were selected as reference models, which reduced the complexity of the full combination of all possible scenarios into those that were represented the most variation.

Watershed Model—AnnAGNPS

Empirical data available from different sources were used as model input for the watershed model, which included: digital elevation model map, soil, rainfall, annual isohyets, land cover, temperature, sky cover, wind speed/direction, and evapotranspiration calculated using FAO method. These data were organized as input files for AnnAGNPS simulation. AnnAGNPS simulated sediment and nutrients due to primary sources of pollutants found in the Hanalei Watershed and they are feral ungulates and alien plants that increase erosion in the upper watershed (increased suspended solids, nutrients, and pathogens), cesspools and septic systems in urban areas, agricultural operations (taro ponds), water bird impoundments, and cattle grazing.

Fuzzy-logic Cognitive Mapping

To develop the ecological model based on the knowledge held by local scientific experts and couple it with the climate and watershed model output, we used a FCM program called Mental Modeler (see www.mentalmodeler.org) (Gray et al. 2013). To construct the conceptual expert model, we held a participatory modeling workshop with four local ecologists who were experts in the three species being modeled followed by two individual meetings with scientific experts to refine the model. One FCM was developed for each of the three endemic species that defined relationships between life-history with habitat variables and variables from the watershed models and predator/prey interactions. As a reference for model building, the workshop used Kauai National Wildlife Management Guidelines and a literature search for each of the three species, watershed variables, predator/prey dynamics, and other relevant factors important.

Fuzzy-logic Cognitive Mapping with the Mental Modeler software includes semi-quantitative models of environmental issues and these models are developed through a three-step process by (1) defining the important system components relevant to an individual or community, (2) identifying the strength of relationships between component pairs, and (3) simulating scenarios on these models to determine how the system as a whole might react under a range of possible
conditions (i.e., system state changes). System components are physical or environmental aspects and may include (1) attributes or characteristics, (2) elements, or (3) processes of a system or place. They are interconnected to represent complex, direct, and indirect interactions or relationships with one another. Relationships between system components indicate the way one component influences or affects another (such as directionality, strength of the relationship, and type of relationship). Relationship directionality is represented in the FCMs as arrows that start at one component and end at another. The relationship arrows may be one-way (uni-directional) or both directions (bi-directional). The strength of the relationship between components may be classified as High (H, strong), Medium (M, moderate), or Low (L, weak), defined either positively or negatively. Positive effects mean that the component the relationship arrow originates from increases the other component. Negative or inverse relationships mean that the component that the relationship arrow originates from decreases the other component. This effect is represented by a plus (+) or a minus (–) symbol following the H, M, or L strength designation (Gray et al. 2013).

**Principal Findings and Significance**

Model results based on IPCC scenarios suggest that increased precipitation will increase Stilt abundance, but decrease Coot and Moorhen abundance. On the other hand, decreasing precipitation may have similar effects across all three species. Additionally, our integrated model scenarios suggests that climate change scenarios will impact life functions (e.g., parental success, breeding, foraging success, etc.) differently across the three species. Combining empirical and expert-based conceptual models allows managers to understand the local ecological impacts associated with global climate change, making it relevant to the management scale. Additionally we suggest this framework can be easily employed by wildlife managers to understand the impacts of climate change on different types of animals and across different ecological conditions.

**Publications Cited in Synopsis**


