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Combining watershed models and knowledge-based models to predict local-scale impacts of climate change on endangered wildlife

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A B S T R A C T

Climate change is expected to have significant impacts on native, threatened and endangered wildlife. Understanding and modeling these impacts useful for wildlife managers, however, remain difficult due to complex climate change, and costly and high data requirements. Consequently, we proposed an easily-interpretable and data-efficient decision support approach to understand climate change impacts on the abundance of three endangered wetland birds (Hawaiian Stilt, Hawaiian Coot and Hawaiian Moorhen). We coupled a watershed model, AnnAGNPS, and ecological models using fuzzy-cognitive mapping software, Mental Modeler, in Hanalei watershed, Kaua'i. Results suggested that increased precipitation would increase Stilt abundance, but decrease Coot and Moorhen abundance. Decreasing precipitation might have negative effects for all three species. Moreover, decision-makers should pay equal attention to controlling components (water depth, food availability and disease) with system-wide influence. Finally, besides being adaptable to similar environmental contexts, our approach captured both direct and indirect climate change impacts through ecological connectivity.

Software availability

Mental Modeler, FCM-based software, is freely available online at www.mentalmodeler.org and can be run in Windows. The lead developer is Steven Gray, Michigan State University, Department of Community Sustainability, East Lansing MI 48823. Email: stevenallangray@gmail.com Phone: 646-915-2915.

AnnAGNPS (Annualized Agricultural Non-Point Source) pollutant loading model software is freely available as a 32-bit version for Windows NT, 2000, XP, 7, and 8, and as a 64-bit version for Windows XP, 7, and 8. AnnAGNPS could also be used on other platforms that have a compiler for ANSI standard Fortran 2008. The executable program is approximately 2 MB. A Pentium or higher PC with a minimum of 32 MB of memory is recommended because of Windows requirements. There is no memory limitation for AnnAGNPS because it includes a memory manager with virtual memory capabilities. Additional free disk storage considerations should include input file and output file needs (and virtual memory if used).

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Information requests, copies of the model, and model documentation can be directed to the AGNPS WEB site at: http://www.ars.usda.gov/Research/docs.htm?docid=5199 or call Fred at 301-869-7195 (email: Fred.Theurer@verizon.net) or Ron at 662-232-2966 (email: Ron.Bingner@ars.usda.gov).

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1. 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), in part due to the difficulties in downscaling and coupling complex global processes with complex local processes (Denman et al. 2007; Friedlingstein et al. 2006; Sitch et al. 2008). As a result, current modeling approaches that allow resource managers to link global processes with local scale dynamics and define the relevant connections between climate change, ecological dynamics, and natural resource management priorities are lacking. 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 are therefore keys if communities are expected to learn about, and collectively adapt to, undesired outcomes associated with environmental change (Pahl-Wastl and Hare, 2004).

One suggested approach to link local scale dynamics to larger processes and address the scale gap is integrating expert based knowledge in the construction of ecological models (Griffiths et al. 2007; Mac Nally, 2007; O'Leary et al. 2009; O'Neill et al. 2008). The value of using expert knowledge in model construction is that experts can help fill the gaps in many complex environmental modeling and decision-making contexts due to insufficient empirical data and highly variable predictions (Kuhnert et al. 2010). Additionally, management decisions may be time sensitive, and institutions may not be able to afford to collect data for robust models. Indeed, recent studies have indicated that expert knowledge can increase the precision of formal data-driven models and facilitate informed decision-making in a cost-effective manner (Kuhnert et al. 2010). Two main modeling methods that bolster traditional forms of ecological models through expert knowledge include Bayesian approaches (Marcot et al. 2006) and Fuzzy-Cognitive Mapping (FCM) approaches (Adriaenssens et al. 2004).

Bayesian approaches have been used to elicit expert knowledge in a range of contexts (Crome et al. 1996; Denham and Mengersen, 2007; James et al. 2010) and incorporated into ecological models. Bayesian ecological models include 1) key components affecting or influencing an ecological aspect, and 2) unidirectional conditional dependencies linking the components. Experts, professional scientists and/or local stakeholder (Zorrilla et al. 2010), describe relevant components probabilistically related to one another based on observed data or personally-held knowledge. Such Bayesian approaches have been applied to resolve wetland degradation conflicts between stakeholders (Zorrilla et al. 2010), and to determine the habitat suitability of the threatened Australian brush-tailed rock-wallaby (*Petrogale penicillata*) (O'Leary et al. 2009).

Similarly, FCM approaches have also been employed to conceptually define relationships in a range of ecosystem contexts characterized by high degrees of complexity and poorly understood causal linkages (Gray et al. 2014). FCMs define a system in terms of: (1) components that comprise the system, (2) bi-directional (including feedback) causal relationships between those components, and (3) perceived degree of influence (positive or negative) that one variable has on another (Kosko, 1987). Contrary to Bayesian approaches, FCMs allow feedback relationships, enabling any additional variable to influence existing components (Jetter and Kok, 2014). Given their flexibility, FCMs are particularly useful for accounting anthropogenic ecosystem impacts, where detailed scientific data is lacking and uncertain but local expert knowledge is available (Nyaki et al. 2014). Furthermore, FCMs have been used to promote public involvement in policy making by informing the public different management options, and enabling a community support for management decisions (Ozesmi and Ozesmi, 2004). Similar to Bayesian models, FCMs enable inclusion of cross-sectoral stakeholder expertise because knowledge of local-scale processes is especially useful for model building and decision-making (Henly-Shepard et al. 2015). Therefore FCMs are useful tools to promote model-based reasoning in a range of decision-making contexts and can be used to understand the ecosystem behavior and its trajectory under different policy options, or environmental or social change scenarios (Marcot et al. 2006; Nyaki et al. 2014; Ozesmi and Ozesmi, 2004). FCMs have been applied to inform management actions for the Lake Erie ecosystem (Hobbs et al. 2002), to understand motivation for bushmeat hunting in Tanzania (Nyaki et al. 2014), to understand the relationship between soil quality and farming dynamics (Halbrendt et al. 2014), and to understand fisheries as a social-ecological system (Gray et al. 2012).

Capturing expert based knowledge in support of ecological decision-making is of particular interest to oceanic islands where climate change is expected to affect many sensitive ecosystems with unique biota (Barnett, 2005), as well as agricultural systems, water resources, human health, infrastructure, and economic performance (Barnett, 2005; Carter et al. 2001; Easterling et al., 2007) although the links between environmental change and impacts to local native ecosystems and human well-being are not always clear. Some general trends have recently emerged (Rosenzweig et al., 2007). For example, decreasing trends in precipitation (~1.1% from 1920 to 2009 at decadal scale) and base flow (Chu et al., 2010; Oki, 2004) will likely impact freshwater ecosystems. Decrease in streamflow (i.e., from 6.7% to 17.2% over the next ~35 years) (Bassiouni and Oki, 2013; Oki, 2004; Safeeq and Fares, 2012) may disrupt life cycle of native aquatic species (Keener et al., 2012). In addition, extreme rainfall events are expected to alter water quality due to changes in nutrient and sediment loadings (Furniss et al., 2010). Despite the trends, Hawai'i's future rainfall projections vary geographically (Keener et al., 2013), and seasonally (Timm et al., 2015). Although these changes are expected to result in further changes to local ecological dynamics, which managers will need to take into account, the impacts are largely uncertain which present considerable decision-making challenges (Denman et al., 2007; Friedlingstein et al., 2006; Sitch et al., 2008).

Although ecologists are beginning to synthesize the cumulative impacts of climate change to island ecosystems (Price et al., 2009), informing mitigation and/or adaptation decisions is not straightforward because of complex island hydrogeology and ambiguous climate change predictions. Current methods to forecast future changes in terms useful for wildlife management are complex because impacts on island communities vary spatially (i.e., windward vs. leeward) and temporally (i.e., wet vs. dry season) (Barnett, 2005). In addition, insufficient understanding of climate change limits social responses (Pahl-Wastl and Hare, 2004), and add uncertainties and complications in decision-making. Consequently, poorly-informed decision-making and failure to reduce associated uncertainties will likely increase the social and ecological costs of climate change on island communities. Therefore, new and improved methods that aggregate several forms of available information are necessary to support decision-making, including probable climate scenarios, empirical data for localized hydrological variation and water resources trends, and expert knowledge of local ecological conditions and dynamics. We suggest that such integrated modeling that uses different forms of data can provide decision-support to natural resource managers currently struggling with the uncertainty associated with understanding the local-scale impacts of global climate change.

Our overarching goal was to develop a modeling approach that coupled biophysical models and expert knowledge models to decrease uncertainty associated with local-scale impacts of climate change within a decision-support framework. Our objective was to develop a locally calibrated watershed model with ecological