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Authors: Lipiec, Eva, Ruggiero, Peter, Mills, Alexis, Serafin, Katherine A., Bolte, John, et al.

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Mapping Out Climate Change: Assessing How Coastal Communities Adapt Using Alternative Future Scenarios

Eva Lipiec[†]*, Peter Ruggiero[†], Alexis Mills[‡], Katherine A. Serafin[†], John Bolte[‡], Patrick Corcoran[†], John Stevenson[†], Chad Zanocco[§], and Denise Lach[§]

[†]College of Earth, Ocean, and Atmospheric Sciences
Oregon State University
Corvallis, OR 97331, U.S.A.

[‡]Biological and Ecological Engineering
Oregon State University
Corvallis, OR 97331, U.S.A.

[§]School of Public Policy
Oregon State University
Corvallis, OR 97331, U.S.A.

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ABSTRACT

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Coastal communities are increasingly experiencing climate change–induced coastal disasters and chronic flooding and erosion. Decision makers and the public alike are struggling to reconcile the lack of "fit" between a rapidly changing environment and relatively rigid governance structures. In efforts to bridge this environment-governance gap in Tillamook County, Oregon, stakeholders formed a knowledge-to-action network (KTAN). The KTAN examined alternative future coastal policy and climate scenarios through extensive stakeholder engagement and the spatially explicit agent-based modeling framework *Envision*. The KTAN's results were further evaluated through a two-step mixed methods approach. First, KTAN-identified metrics were quantitatively assessed and compared under present-day *vs*. alternative policy scenarios. Second, the feasibility of implementing these policy scenarios was qualitatively evaluated through a review of governmental regulations and semistructured interviews. The findings show that alternative policy scenarios ranged from significantly beneficial to extremely harmful to coastal buildings and beach accessibility in comparison to present-day policies, and they were relatively feasible to almost impossible to implement. Beneficial policies that lower impacts of flooding and erosion clearly diverge from the existing regulatory environment, which inhibits their implementation. In response, leadership and cross-sector cooperation and coordination can help to overcome mixed interests and motivations, and increase information exchange between and within the public and government organizations. The combination of stakeholder engagement, an alternative futures modeling framework, and the robust quantitative and qualitative evaluation of policy scenarios provides a powerful model for coastal communities hoping to adapt to climate change along any coastline.

ADDITIONAL INDEX WORDS: *Climate change, adaptation, Envision, coastal hazards, coastal futures, Oregon coast, Tillamook County, scenario planning*.

INTRODUCTION

The physical world, as we have known it, is changing. Coastal communities around the world are grappling with chronic tidal or "nuisance" flooding (*e.g*., Sweet *et al*., 2014), devastating hurricanes (*e.g*., Hapke *et al*., 2013), and extreme high water levels, such as those seen during the El Niño winters along the U.S. West Coast (*e.g*., Allan and Hart, 2008; Barnard *et al*., 2011, 2015). The impacts of these events range from the physical, (*e.g*., chronic to catastrophic coastal flooding and erosion) to the economic (*e.g*., increased costs to construct and maintain backshore protection structures [BPS], beach nourishment, *etc*.) to the social (*e.g*., beach closures, reduced scenic value, *etc*.). Impacts are projected to continue to increase due to sea-level rise (SLR; IPCC, 2013; Komar, Allan, and Ruggiero, 2011; NRC, 2012), changes in storminess patterns (Allan and Komar, 2006; Hemer *et al*., 2013; Ruggiero, Komar, and Allan, 2010), and possible variations in the magnitude and frequency of El Niño events (Cai *et al*., 2014).

The struggle to manage the effects of climate change on an expanding coastal population is confounded by the lack of "fit" between the dynamic economic, social, and environmental characteristics of coastal communities (Folke *et al*., 2007) and their relatively static and inflexible governance and planning structure (Johnson and Schell, 2013). This mismatch between dynamic systems and static governance structures suggests that a barrier exists to implementing the adaptation policies necessary to limit impacts and improve a coastal community's adaptive capacity, defined here as the ability of any system to increase and/or maintain the quality of life of its members (Dutra *et al*., 2015; Galaz *et al*., 2008; Gallopin, 2006; Millennium Ecosystem Assessment, 2006; Pittman *et al*., 2015).

Actions specifically focused on increasing a community's adaptive capacity are a relatively recent phenomena, a part of the recognition that communities are experiencing growing exposure and sensitivity in a changing environment (Coletti *et al*., 2013; Folke, 2006; Garmenstani, Allen, and Benson, 2013). Community adaptive capacity is influenced by a variety of

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*Corresponding author: eva.lipiec@gmail.com

factors, including management practices, access to financial, technological, and informational resources, current infrastructure, and present institutions, political influence, and kinship networks (Smit and Wandel, 2006). Ultimately, improving the fit between an evolving complex environment and a static government structure by modifying laws and regulations can increase the adaptive capacity at the community level (Dietz, Ostrom, and Stern, 2003; IPCC, 2013; Pittman *et al*., 2015).

This paper describes a step-by-step approach to increase the capacity of coastal communities to adapt to chronic hazards by combining deep stakeholder engagement, a powerful alternative futures modeling platform, and robust evaluation of policy and coastal hazard scenarios. The paper has four main objectives:

(1) describe how social and environmental landscape data were integrated with stakeholder-developed land-use adaptation policies and century-long climate change projections within the publicly accessible multi-agent model *Envision* (Bolte *et al*., 2007, http://envision.bioe.orst.edu/);
(2) explore the potential quantitative impacts of the various adaptation policies considered by assessing the differences in timing, magnitude, and benefits of continuing current policies (the status quo) *vs*. alternative policy scenarios;
(3) characterize the feasibility of, barriers to, and factors associated with successful adaptation policy implementation within the current social and policy environment of Tillamook County, Oregon; and
(4) evaluate the "fit" between beneficial adaptation policies and possible limitations to their adoption.

The paper is organized as follows: First, background material on the need for and current state of adaptation planning within Tillamook County is introduced. Next, the "Methods" section provides a description of the mixed methods approach used to assess the codeveloped adaptation policies under different future climate impact scenarios. The "Results" and "Discussion" sections quantitatively and qualitatively evaluate the significance and feasibility of these policy scenarios. Finally, the "Conclusion" summarizes the findings and discusses their broader implications.

Setting

Spanning ~100 km of northern Oregon, the Tillamook County coast is a popular location for full- and part-time residents and visitors to enjoy the ecological, recreational, and aesthetic features of the Pacific Northwest (PNW) beaches (Figure 1). The coast is composed of sandy, dissipative, dune-backed beaches, punctuated by rocky headlands. Communities along the coastline experience chronic winter coastal flooding and erosion (Allan and Hart, 2007; Allan and Priest, 2001; Allan *et al*., 2015; Cheng, Hill, and Garcia-Medina, 2015; Cheng, Hill, and Read, 2015; Ruggiero *et al*., 2013) when high water levels collide with or overtop dunes and/or backshore protection structures (BPS), such as riprap revetments. These high total water levels (TWLs) are a consequence of a combination of big waves and storm surge during large storm events, sea-level anomalies due to El Niño events and other climatological phenomena, and astronomical tides (Serafin and Ruggiero, 2014).

Increasing wave heights have been observed in the north-eastern Pacific during analyses of instrumented National Buoy Data Center buoys along the U.S. West Coast (Allan and Komar, 2000, 2006; Ruggiero, Komar, and Allan, 2010; Mendez *et al*., 2006; Menendez *et al*., 2008) and satellite altimetry (Young, Zieger, and Babanin, 2011). Coastal hazards in the region are punctuated by the occurrence of major months-long El Niño events, which raise sea levels as much as 30 cm, change wave direction, and cause "hotspot" or anomalously high rates of localized erosion (Barnard *et al*., 2017; Kaminsky, Ruggiero, and Gelfenbaum, 1998; Komar, 1998).

Like elsewhere, coastal hazards in Tillamook County are expected to worsen in the future due to climate change factors, including SLR, changes to storminess patterns, and possible changes in the magnitude and frequency of El Niño events. After accounting for tectonic influence on land-level changes, relative sea levels along Oregon's coast are projected to rise between approximately 10 cm and as much as 1.4 m by the year 2100 (NRC, 2012; Strauss, 2013). While there is no strong consensus about modifications to the wave climate due to climate change (*e.g*., Erikson *et al*., 2015; Hemer *et al*., 2013; Wang, Feng, and Swail, 2014), recent increasing wave heights have been shown to have a more significant role in the growing frequency of coastal flooding and erosion in the PNW than the concurrent SLR (Ruggiero *et al*., 2013). Finally, while El Niño events are expected to remain an important driver of interannual climate variability globally (IPCC, 2013), there is little consensus on whether the frequency and intensity of these events may increase, decrease, or remain unchanged in the future (Cai *et al*., 2014; Cane, 2005; Ruggiero *et al*., 2010; Santoso *et al*., 2013; Vecchi and Wittenberg, 2010).

Coastal Climate Change Adaptation in Tillamook County

Around the world, stakeholders are grappling with how to understand dynamic landscapes and changing community vulnerability. The abundant research and planning in both developed (*i.e*. other parts of the United States—Kashem, Wilson, and Van Zandt, 2016; Kleinosky, Yarnal, and Fisher, 2007; Australia—Sahin *et al*., 2013; United Kingdom—DEFRA, 2006; and The Netherlands—de Moel, Aerts, and Koomen, 2011) and developing countries (i.e., 18 locations—Sherman and Ford, 2013; and Papua New Guinea—Butler *et al*., 2015) have focused on various parts of the coastal climate change adaptation puzzle, at times combining population changes, flood projections, stakeholder input, and social vulnerability assessments.

In the United States, as mandated by the Coastal Zone Management Act of 1972, coastal zone management is different depending on the state, county, and local towns in question. At the state level in Oregon, public ownership and access to the beach are regulated by Oregon's common law and the 1967 "Beach Bill," which ensures public ownership of the beach up to the mean high water line and allows public access up to the vegetation line. Several state agencies maintain these public rights through the creation and

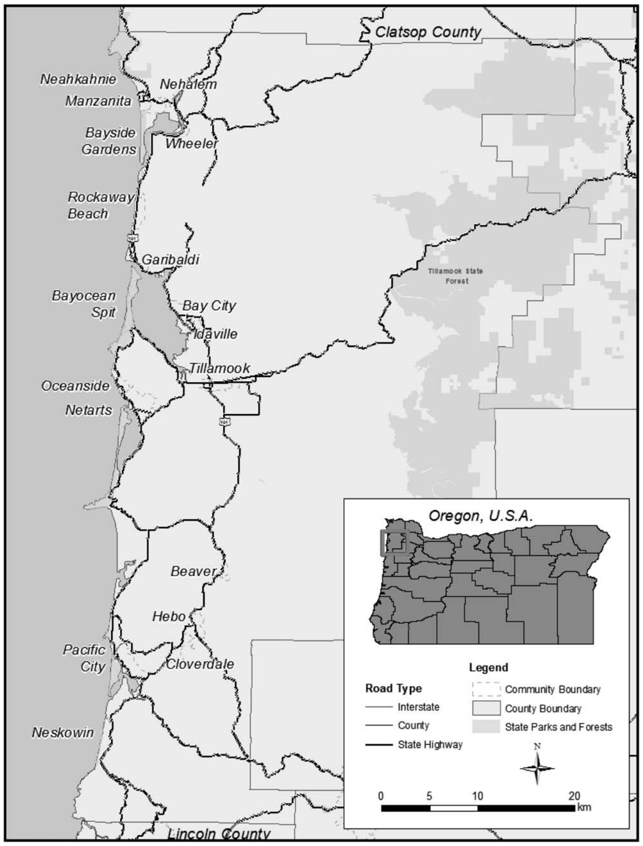

Figure 1. Map of Tillamook County, Oregon, showing the location of coastal communities and major roads, including the town of Neskowin.

enforcement of Statewide Planning Goals, under which property owners may petition to build BPS on eligible properties. Yet, as SLR, larger waves, and El Niño events continue to occur, the private right to build BPS (and subsequent encroachment onto public space) will increasingly clash with the public's right to the beach.

Historically, efforts to minimize the impacts of coastal hazards and climate change in Tillamook County have been piecemeal, dependent on individual property owners and emergency measures (Clarke *et al.*, 2013; Folke, 2006). A rare example of locally driven, community-wide adaptation planning took place in the unincorporated community of Neskowin (~5 km of coast, population <200) in southern Tillamook County (Figure 1). The efforts of Neskowin stakeholders, resulting in a plan ratified by the county in 2014, served as a catalyst for work throughout the county.

METHODS

A mixed methods approach (Driscoll *et al.*, 2007; Jick, 1979) was developed to analyze both the quantitative and qualitative information generated by *Envision* and the Tillamook County Coastal Futures knowledge-to-action network (TCCF KTAN) process. The following sections present methods used to (1) quantitatively model projections of development, coastal flooding, and coastal erosion under a variety of climate and policy scenarios in *Envision*, (2) quantitatively assess the timing, magnitude, and benefits of differences between the status quo and alternative policy scenarios, and (3) qualitatively characterize barriers to and factors for successful adaptation policy implementation.

Tillamook County Coastal Futures Knowledge-to-Action Network

To begin to consider proactive approaches to adapting to climate change–induced coastal hazards, the TCCF KTAN was formed in 2012. The KTAN was composed of interested volunteers from varying departments of state, county, and local agencies, nongovernmental organizations, private citizens, researchers, students, and outreach specialists. Using the agent-based modeling framework *Envision*, the KTAN was interested in evaluating how different adaptation policies and effects of climate change may impact the Tillamook County coastal landscape in the future (Bolte *et al.*, 2007; Hulse, Branscomb, and Payne, 2004). The combination of significant stakeholder engagement and data sets, and quantitative analysis of policy and climate scenarios in *Envision* (Figure 2) allowed for the evaluation of adaptation strategies in light of future uncertainty (Clarke *et al.*, 2013; Evans *et al.*, 2013; Poumadere *et al.*, 2015; Tompkins, Few, and Brown, 2008). Results generated could therefore be deemed scientifically and publicly "credible," "salient," and "legitimate" (Cash *et al.*, 2003).

Initial KTAN meetings and literature reviews identified adaptation policies encompassing a range of common measures, including: coastal retreat of population centers, construction of BPS, use of beach nourishment, *etc*. Policies chosen were grouped into four scenarios: status quo (continuation of present-day policies), hold the line (policies that resist environmental change in order to preserve both infrastructure and human activities), realign (policies that change human activities to suit the changing environment), and laissez-faire (relaxation of current limiting policies; Supplementary Material Table S1). The KTAN also requested the evaluation of impacts under the county-scale implementation of the town of Neskowin's adaptation policies (Supplementary Material Table S1). Finally, flooding and erosion impacts under the five policy scenarios were presented at workshops to further incorporate stakeholder suggestions, evaluate model assumptions, and rate outcomes, forming the sixth policy scenario, hybrid (Supplementary Material Table S1).

Modeling Coastal Futures within *Envision*

Baseline data sets describing population growth and development patterns, SLR, coastal flooding and erosion, and adaptation policies were incorporated within *Envision* to project alternative futures on an assortment of geographical (community to county) and temporal (yearly from 2005 to 2099) scales (Mills, 2015); see Figure 2. Impacts to the natural and built environment were modeled with 100 m resolution in the alongshore and 10 m resolution in the cross-shore direction—scales fine enough to resolve impacts to individual homes and businesses yet coarse enough to support large-scale (~100 km, ~100 years) probabilistic simulation techniques.

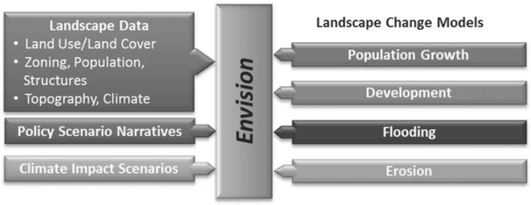

Figure 2. Data sets, models, and metrics of the modeling framework *Envision*, modified from Bolte *et al.* (2007).

Population Growth and Development

Using 2013 Oregon Office of Economic Analysis (2013) estimates of future growth, an additional 12,000 new residents were allocated to Tillamook County throughout the twenty-first century based on the current distribution of the population and local zoning ordinances. Future growth was further regulated by individual policies within the policy scenarios.

Coastal Hazards Modeling

At any given time, the elevation of the total water level (TWL), relative to a fixed datum, is composed of mean sea level, the deterministic astronomical tide, nontidal residuals, and wave runup:

$$Total\,Water\,Level\,(TWL) = MSL + \eta_A + \eta_{NTR} + R \qquad (1)$$

where, MSL is the mean sea level, η_A is the deterministic astronomical tide, η_{NTR} is the nontidal residuals, and R is the wave-induced runup (Ruggiero *et al.*, 2001; Serafin and Ruggiero, 2014; Stockdon *et al.*, 2006). In order to robustly estimate extreme TWLs, multiple synthetic records of each TWL component, and their dependencies (*e.g.*, extreme wave heights and storm surges often occur together), were generated with the total water level full simulation model (TWL-FSM) of Serafin and Ruggiero (2014). The TWL-FSM produces various combinations of events, some of which may not have occurred in the observational record due to record length.

Using this modeling approach, 45 synthetic time series of daily maximum TWL over 95 year (2005–99) durations were simulated for every alongshore model grid node in Tillamook County. The potential for flooding and erosion along Tillamook County outer coast beaches was first determined using Sallenger's (2000) Storm Impact Scale, which assesses the elevation of TWLs relative to elevations of important backshore features such as BPS features or dune toes or crests. While the Storm Impact Scale model has four storm-impact regimes, the focus is on two of the regimes: collision (BPS/dune toe $<$ TWL $<$ BPS/dune crest), in which the TWL is impacting the backshore feature, resulting in erosion, and overtopping (TWL $>$ BPS/dune crest), in which the TWL is over the BPS/dune crest, and the possibility exists for flooding of the backshore (Sallenger, 2000). Beach and dune morphometrics, such as backshore crest location and height, were extracted from high-resolution LIDAR data sets and topographic surveys (Mull and Ruggiero, 2014; Watershed Sciences, 2009a; Watershed Sciences, 2009b).

When the TWL exceeded the backshore elevations and resulted in overtopping, flooding extents were computed using a simple hydraulic connectivity model. Estimates of cross-shore coastal retreat were computed annually and calculated using the approach developed by Baron *et al.* (2014), which accounted for both event-based and long-term coastal change:

$$CCH_p = (CCR_{SB} + CCR_{SLR}) \times T + CC_{event} \qquad (2)$$

where, CCH_p is the coastal change hazard projection associated with a particular year of interest, T, and the maximum yearly TWL event. CCR_{SB} is the long-term (interannual to decadal-scale) coastal change rate associated with sediment budget factors (*e.g.*, gradients in longshore sediment transport, changes in sediment supply due to engineering structures) and was modeled simply by linearly extrapolating observed historical shoreline change rates (Ruggiero *et al.*, 2013). CCR_{SLR} is the long-term coastal change rate associated with SLR and was modeled here *via* the Bruun Rule (Bruun, 1962). Conservatism was built into the projection by the inclusion of an event-based coastal erosion term associated with a significant storm event, CC_{event}, added to the projected long-term evolution (Baron *et al.*, 2014; Revell *et al.*, 2011). Estimates of event-based potential foredune erosion were computed using the equilibrium dune erosion model of Kriebel and Dean (1993), which Mull and Ruggiero (2014) found well-suited for PNW conditions and available data. While the coastal flooding and change hazards models implemented in *Envision* are relatively simple, the approach was designed to be modular and allows for the implementation of more sophisticated models when warranted.

Policy and Climate Impact Scenarios

To quantitatively model the qualitative TCCF KTAN–developed policy scenarios, various assumptions were used to represent human decision making within *Envision*. For example, buildings were considered to be impacted by flooding if they were within 10 m of floodwaters. Many additional assumptions were made within the model and are discussed as they discernibly impact the results.

Using the TWL model described above, each policy scenario was modeled for 95 years (2005–99) under three different climate impact scenarios based on low, medium, and high SLR projections. The three climate impact scenarios were based upon National Research Council (NRC) SLR estimates for Oregon and Washington (Figure 3), which ranged from 0.1 m to 1.4 m by the end of the century (NRC, 2012). Possible changes in storminess patterns, *i.e.* variations in mean and maximum significant wave heights (SWH), were estimated by shifting SWH distributions using future estimates of SWH change from global climate model projections (Hemer *et al.*, 2013; Wang, Feng, and Swail, 2014). The frequency of major El Niño events was allowed to vary between half as often to twice as often as present-day conditions. Fifteen random variations of wave heights × El Niño conditions were modeled for each climate impact scenario for a total of 45 simulations of future TWLs per policy scenario per year (Figure 3).

Approximately 120 metrics representing changes to the built and natural environment due to future growth and development, extreme TWLs, impacts of flooding and erosion, and the implementation of adaptation policies were quantified and tracked within *Envision*. Of these metrics, stakeholders

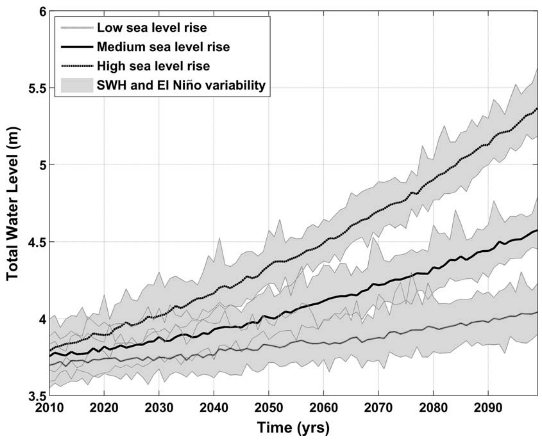

Figure 3. Regional estimated SLR and SWH for the twenty-first century. The bold lines represent low, medium, and high estimates of SLR for the Oregon and Washington coast for 2010 to 2100 as estimated by the National Research Council (NRC, 2012). The gray area around the lines represents El Niño and SWH variability. The mean of the log-normally distributed SWH climate was allowed to randomly shift ±30 cm in either direction within each subclimate simulation in accordance with the range of variability from downscaled global climate projections (Hemer *et al*., 2013; Wang, Feng, and Swail, 2014).

identified eight metrics of most importance (Table 1), which served as the basis for further statistical assessments, described below. Further information about modeling the policy and climate scenarios can be found in the Supplemental Material Additional Resources section.

Statistical Assessment of *Envision* Outcomes

The differences between metric values due to various policy scenarios can oftentimes be appreciated visually (Figure 4). However, to determine true differences in timing and magnitude, a cross-sectional regression model was employed using value transformations to normalize unequal variance between policy scenarios (Ramsey and Schafer, 2002). Metric values under alternative policy scenarios were considered different than the status quo over the long term when two additional conditions were satisfied. First, a significant difference ($p < 0.5$) was present and sustained over a period of time (nine of the subsequent 10 years). This definition of a statistically different period allowed random climate variability to occur but ensured that policy outcomes significantly differed on a decadal scale. Second, the statistically significant difference had to be sustained for >67% of the remaining time after the first instance of significance.

If metric values met these two conditions, the magnitude of the change between the status quo and the alternative policy scenario was calculated as the average difference from the first instance of sustained significance to the end of the century for each metric. This calculation helped to describe the general trends among the policy scenarios over time and climate variability. Finally, alternative policy scenarios were deemed beneficial if they lessened the impact of flooding or erosion upon a metric. The quantitative benefit of a policy scenario was estimated as the number (or percentage) of sustained metrics that lessened flooding and erosion due to the alternative policy scenario.

Policy Assessment

While determining the timing, magnitude, and potential benefits of sustained statistical difference between policy scenarios is important, decision makers and stakeholders are also interested in the feasibility of implementing various adaptation policies in the current regulatory environment (Gleason *et al*., 2010). A first-order characterization of barriers to the implementation of the adaptation policies was completed through a review of current incorporated and unincorporated city, county, and state planning documents, and federal agency (*e.g*., Federal Emergency Management Administration, U.S. Army Corps of Engineers, *etc*.) regulations.

A secondary characterization of feasibility was completed *via* 10 semistructured interviews conducted with senior managers, planners, local stakeholders, and scientists from 15 local, county, and state agencies and organizations. Using a snowball method (Robson, 2011), organizations involved with the TCCF KTAN were interviewed first and asked to identify additional groups to interview; the final organizations represented a variety of geographical scales, interest groups, and governmental levels related to the coastal environment. Interviews focused on characterizing the feasibility of implementing the stakeholder-developed adaptation policies by identifying both the greatest challenges to and the necessary factors for successful policy implementation. The groups were also asked to indicate whether government approval or modifications to statutory or regulatory documents would be necessary to implement the policies at five governmental levels: unincorporated community, incorporated city, county, state, and federal.

Feasibility was quantitatively estimated as follows: Policies that would require governmental approval or modifications to regulatory documents were assigned a value of one, while those that did not require approval or modifications received a value of zero. If the need for approval or modifications was unclear, the policy was assigned a score of 0.5. Once evaluated, average ratings were calculated across governmental levels and policy scenarios. Policy scenarios with higher averages indicated that the scenario was less feasible than those scenarios with lower averages. Once the barriers to and factors for successful policy implementation were isolated, the thematic responses were tallied and further evaluated through the use of a framework created by Dutra *et al*. (2015), based on a similar interview process in coastal Australia. Further information about the statistical and policy assessments described here can be found in the Supplemental Material Additional Resources section.

RESULTS

In the following sections, the projected time series for the eight Tillamook County–wide flooding and erosion metrics of interest are described and differentiated across six policy and three climate impact scenarios. Barriers to and components for successful policy implementation, as suggested by the policy review and interviews, are also described.

Table 1. *Stakeholder chosen metrics of interest.*

Metric	Description
Beach Accessibility (%)	Percentage of each year that maximum daily TWLs did not impact the base of the dune/BPS within each model grid cell.
Length of Road (in km) Impacted by Flooding ("Roads Flooded")	Length of local, county, and state roads affected by flooding per year.
Length of Road (in km) Impacted by Erosion ("Roads Eroded")	Length of local, county, and state roads affected by erosion per year.
Number of Buildings Impacted by Flooding ("Buildings Flooded")	Number of buildings that are impacted by flooding per year (within a 10 m buffer area).
Number of Buildings Impacted by Erosion ("Buildings Eroded")	Number of buildings impacted by event-based erosion per year (within a 10 m buffer area).
Number of Buildings "Destroyed" by Erosion ("Buildings Destroyed")	Number of buildings "destroyed" each year as chronic erosion shifts the shoreline landward through beachfront properties.
Value of Property ($ in millions) Impacted by Flooding ("Value Flooded")	Total value of properties impacted by flooding per year (in 2010 dollars).
Value of Property ($ in millions) Impacted by Erosion ("Value Eroded")	Total of properties impacted by erosion per year (in 2010 dollars).

Envision Modeling Results

Visually, the eight stakeholder-chosen metrics displayed considerable annual to decadal variability, but there were trends clear over time. For example, the *Number of Buildings Impacted by Flooding* metric exhibited high annual variability due to the impacts of changes to SWHs and El Niño frequency for each of the policy scenarios (Figure 4, top panels). Meanwhile, increased sea level over the course of the century and across the three climate impact scenarios resulted in growing numbers of buildings impacted across the majority of policy scenarios (Figure 4, top panels). The lowest impacts to buildings by flooding occurred in the low-impact climate change scenario under the realign and hybrid policy scenarios (Figure 4, top panels) due to the influence of a policy that prevents BPS construction. When SLR and BPS construction co-occur, the beach slope steepens. A steepened beach works as a ramp, causing increased TWLs. The realign and hybrid policy scenarios moved buildings away from the shoreline as they were impacted by hazards and did not allow the construction of BPS and subsequent beach steepening, resulting in a signifi-

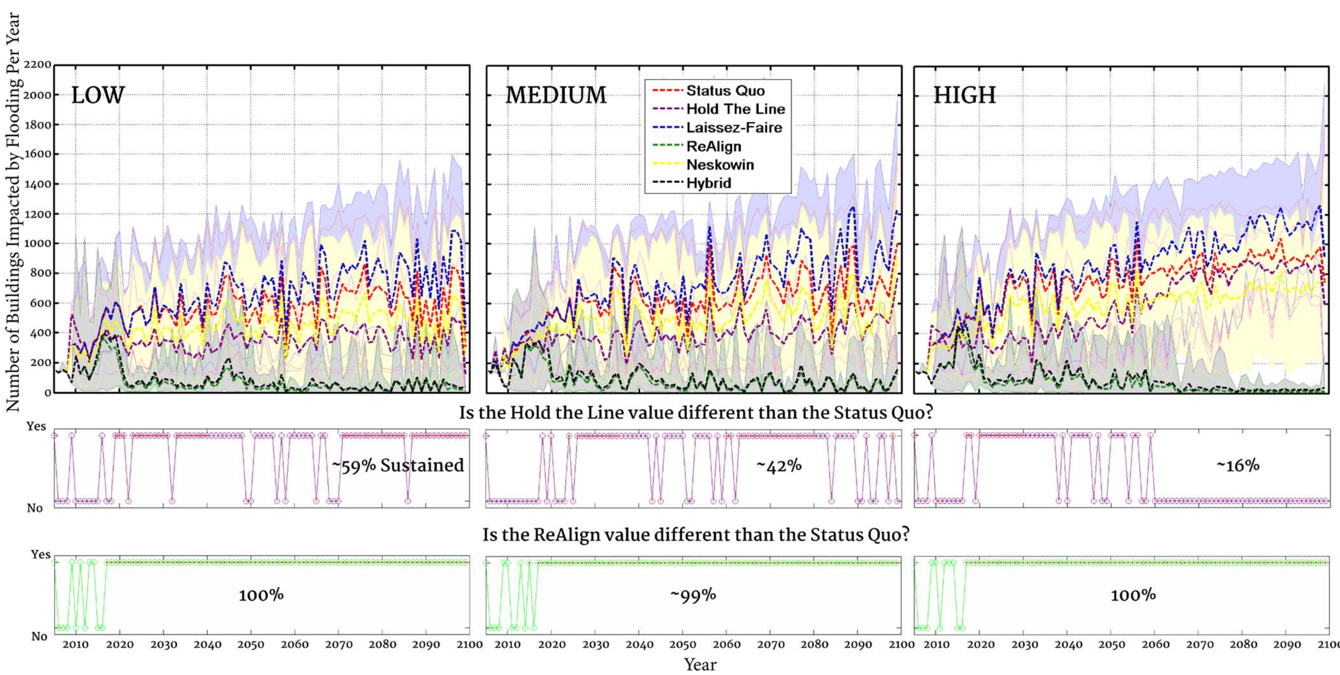

Figure 4. Top panels: The number of buildings impacted by flooding per year under the six policy scenarios, and low-, medium-, and high-impact climate change scenarios (with 15 simulations in each). The dashed bold lines for each policy scenario denote the mean metric values under each climate impact scenario. The shaded areas highlight the average minimum and maximum values under each climate impact scenario; *e.g.,* within the low-impact climate change scenario, the green shaded area denotes the range of buildings impacted by flooding under a realign policy scenario between the average highest values of 15 the subclimate simulations and the average lowest values of the 15 subclimate simulations. It is important to note that homes may or may not be rebuilt, depending on the policy scenario in question (*e.g.,* assumed rebuilding under hold the line scenario; homes not permitted to be rebuilt under realign scenario; please see Supplementary Material for more information). Bottom panels: The statistical differences between the hold the line and realign policy scenarios in comparison to the status quo. Points in time highlighted with red dots represent years where the alternative policy scenario values are statistically different than the status quo, with percentages noting how long statistical difference was sustained over the remainder of the century. (Color for this figure is available in the online version of this article.)

cant reduction in the number of impacted buildings (Figure 4, top panels).

It is important to note that differences in modeling method sensitivity resulted in a larger range of resulting values for flooding hazards than erosion hazards. Overall, only one metric increased across all policy scenarios and climate scenarios: the *Length of Road Impacted by Flooding*. Impacts to the remaining metrics were more variable (as illustrated in Figure 4, top panels), with many policy scenarios incurring both positive and negative effects. Overall, the laissez-faire policy scenario had the most negative impact on flood-related metrics (*i.e. Number of Buildings Impacted by Flooding*), while the realign and hybrid policy scenarios performed most poorly in erosion-related metrics (*i.e. Number of Buildings Impacted by Erosion*).

Statistical Assessment

No alternative policy scenario achieved sustained statistical difference from the status quo in all eight of the metrics of interest (for example of sustained statistical difference, see Figure 4, bottom panels). The hybrid policy scenario statistically altered the greatest number of metrics (seven in the high-impact climate change scenario), while the hold the line policy scenario changed the least (one metric in the medium- or high-impact climate change scenarios; Figure 5). The remaining alternative policy scenarios impacted three to six metrics. The alternative policy scenarios became statistically different from the status quo within the first third of the century on average (Figure 5). This timing indicates that if implemented, alternative policies could impact the landscape within the next 25 years.

According to the conditions set and the metrics chosen by the stakeholders, both the most and least beneficial policy scenarios reduced metrics related to erosion: The laissez-faire policy scenario improved 42% of the metrics considered, at a rate of 56%–62% improvement, while the hold the line policy scenario improved only 21% of the metrics at a rate of 63%–96% (Figure 6). Both of these policy scenarios, and the Neskowin policy scenario, did not statistically increase flooding impacts. The remaining alternative policy scenarios varied in their positive and negative impacts (Figure 6).

Policy Assessment

In addition to the statistical analysis, each individual policy was assessed for its feasibility. To do so, individuals from 15 state, county, and local agencies and organizations were asked for policy ratings and characterizations in conjunction with a literature and legal document review of state, county, and local land-use planning ordinances.

Implementation Feasibility

Information collected from the interviews and literature review facilitated the implementation feasibility rating (zero to one) of each individual policy and collective policy scenario. As expected, the status quo policy scenario, which required no alterations to current regulation and policy, was deemed the most straightforward to implement with a rating of zero. Conversely, the laissez-faire policy scenario, which required the greatest changes to current regulation (including the removal of a statewide planning regulation) was rated the most difficult to implement with a rating of 0.80. The hold the line policy scenario was rated the second most straightforward set of policies to implement, buoyed by the lack of regulatory barriers to continued BPS construction and beach nourishment. Ratings for the three remaining policy scenarios (realign, Neskowin, and hybrid) were relatively similar (0.56, 0.50, 0.61, respectively), which is an artifact of multiple overlapping policies that restricted land use and moved development away from the coastline.

Barriers to Policy Implementation

Respondents identified a total of 18 general barriers to adaptation policy implementation. The majority of barriers were not unique to the field of coastal climate change adaptation, having been identified and categorized in other natural resource settings (Aylett, 2014; Dietz, Ostrom, and Stern, 2003; Dutra *et al*., 2015; Gupta *et al*., 2010; Pittman *et al*., 2015). Dutra *et al*. (2015) provided a particularly useful framework for identifying and characterizing barriers to implementation, including (in order of number of mentions from the Tillamook County interviewees): (1) interests and motivation, (2) information and knowledge, (3) organizational structures, (4) leadership, and (5) resources. Additional Tillamook County barriers not cited in Dutra *et al*. (2015) were also uncovered during the interviews. Responses were grouped thematically, with organizations voicing numerous challenges to implementation that could fall within one type of barrier (see numbers in parentheses in the following paragraphs); only barriers that were mentioned 10 or more times are discussed in detail here and in Table 2.

A group's interests and motivation, composed of their limited learning capacity and perceptions and assumptions (Dutra *et al*., 2015), were identified as the most common limitations (26 mentions) to implementing adaptation policies (Table 2). Within this barrier, poor perception and distrust of and/or assumptions about the government and its intentions, a sentiment echoed in other U.S. locations and other democratic societies (Clarke *et al*., 2013; Milligan and O'Riordan, 2007), was mentioned by all organizations (15). Additional barriers of perception and assumption were noted in terms of a lack of proactive or anticipatory thinking and a reliance on disaster-driven policy creation (Godschalk *et al*., 1998) (4), limited learning capacity (*i.e*. subject fatigue) (3), hesitancy to consider policies due to socioeconomic status, occupation, political affiliation, length of residency, *etc*. (2), the perceived future timing of climate change effects (1), and the cultural or social differences between coastal communities with varying levels of climate change impacts and adaptation knowledge (1).

The next most common categories were the barriers imposed by inadequate information and knowledge, and the present structure of government organizations (11 mentions each) (Table 2). In Tillamook County, as elsewhere (Aylett, 2014; Clarke *et al*., 2013; Sheppard *et al*., 2011), interviewees noted the public's lack of knowledge of land-use policies, climate, and coastal hazards (8), their poor understanding of the differences between coastal flooding/erosion and tsunami hazard zones (2), and inadequately prepared geologists/engineers (1).

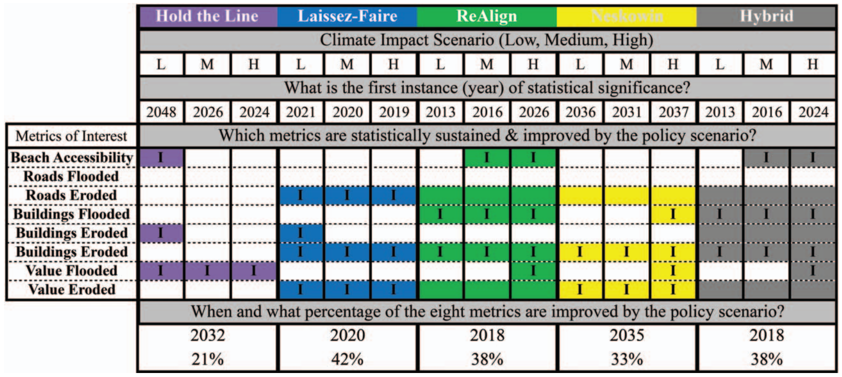

Figure 5. How policy scenarios change the metrics over the course of a century, showing average year of first instance of sustained statistical difference compared to the status quo under each climate impact scenario, metrics that sustained their statistical difference from the status quo under each policy and climate impact scenario (and metrics that improved, *e.g.,* less flooding and erosion, as denoted by the "I"), and the percentage of the metrics that were improved across all climate impact scenarios. Full descriptions of the metrics can be found in Table 1. Full policy scenario descriptions are included in the Supplementary Material. (Color for this figure is available in the online version of this article.)

In terms of organizational structures, Tillamook County interviewees remarked on the structural inflexibility of state agencies and county regulations (4), poor coordination or "siloing" between agencies and groups due to financial or bureaucratic constraints (3), a disconnect between decision makers at the state and county levels (2), and separate regulations between city and unincorporated areas (2).

In addition to the barriers described above, organizations identified challenges due to a lack of leadership and external pressures on leaders (6), an absence of financial, technical, and human resources (4), and an additional Tillamook County–specific limitation not cited within the Dutra *et al.* (2015) framework: frustration with the unpredictability of state legislature decision making (1).

Attributes of Implementation Success

Organizations identified several successful examples of adaptation policy implementation, with a number of key factors, similar to those found in earlier studies by Dietz, Ostrom, and Stern (2003), Dutra *et al.* (2015), Gupta *et al.* (2010), and Pittman *et al.* (2015). Respondents provided a total of 18 components of success, several of which fell into more than one category. Attributes of success included (categories from Dutra *et al.*, 2015): (1) leadership, (2) cross-sector cooperation and coordination, (3) effective integration of knowledge and insights, (4) human capacity and coordinated participation in decision making, and (5) learning approach to natural resource management and governance (Table 3). Once again, only attributes that received 10 or more mentions are discussed here.

Successful leadership includes communication and collaboration, trust, and transparency in the management process (Dutra *et al.*, 2015). Several interviewed organizations believed those in positions of leadership have the responsibility to help foster ongoing conversations to ensure that the decision-making process is inclusive and fair (15 mentions) (Table 3). Effective leaders were able to identify and disseminate available funding, information, and man-power (5), increase and continue public understanding and focus through outreach and education measures (4), act as champions at multiple governmental levels (3), especially through the use of political capital (2), and facilitate discussion through low-controversy methods (1). No organization noted the third Dutra *et al.* (2015) component of leadership, transparency in management, as a requirement of success, possibly due to the open nature of Oregon policy-making as required by state law.

The next most highly cited attribute of success in Tillamook County was cross-sector cooperation and coordination (11) (Table 3). The cross-sector cooperation and coordination category consists of autonomy and redundancy in authority and capability, flexibility, and definition of roles and responsibilities (Dutra *et al.*, 2015; Gupta *et al.*, 2010; Milligan and O'Riordan, 2007). Tillamook County respondents, and coastal managers in other locations, noted the need for top-down guidance combined with autonomy at the local level (7) and the flexibility to use alternative strategies and tailor regulations to a variety of scales (4) (Gupta *et al.*, 2010; Kettle and Dow, 2014). Clearer definitions of agency roles and responsibilities were not cited as necessary successful factors by the interviewees, which may be due to the existence of the Statewide Planning Goals and required comprehensive county land-use plans.

In addition to the components cited above, organizations identified several other factors for success in Tillamook County and elsewhere. Successful policy implementation was dependent upon the use of appropriate outreach, engagement, and visual aids (6), human capacity (*i.e.* sustained interest), coordination, available funding, organizational knowledge, and bridging organizations (5), and, not cited in Dutra *et al.* (2015), external forces and changes such as county demographics, pressure to adapt *via* insurance regulations, and the presence or absence of a receptive higher level of government. No organizations cited the need for a better planning framework, a lack of resource ownership, or the absence of

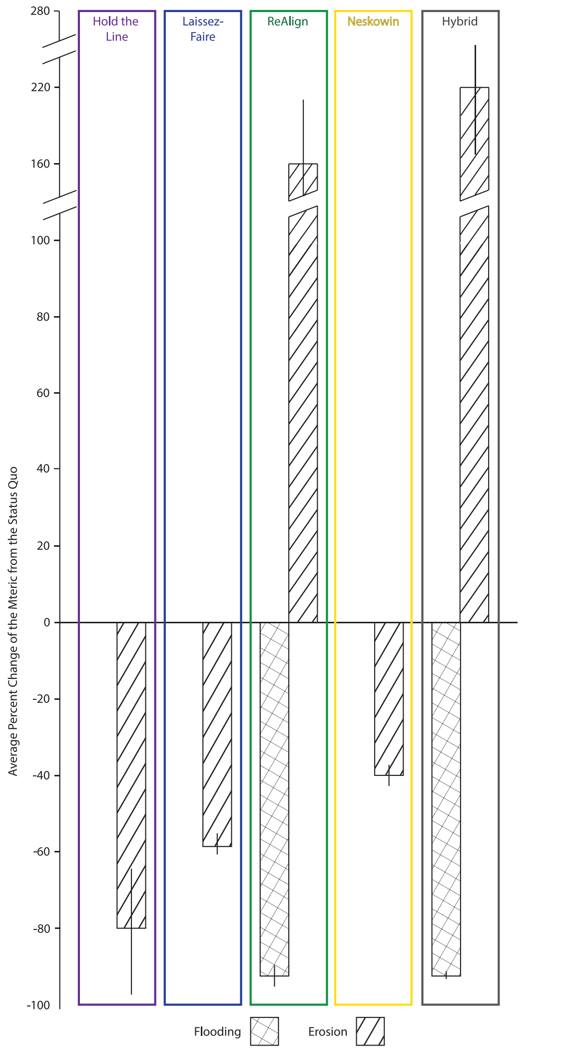

Figure 6. How much flooding and erosion metrics are impacted by the policy scenario, showing the percent change difference in impacts between the status quo and each alternative policy scenario in terms of flood or erosion metrics, *e.g.,* while the laissez-faire policy scenario improves 42% of the metrics, the largest changes occur in the erosion-related metrics, where there are on average ∼60% less impacts to the number of homes, length of roads affected, and value of property. Metrics below the zero line experience less impacts due to the policy scenarios, while metrics above the line experience more impacts due to the policy scenarios. Note: (1) The flooding bars are an average of the percent changes within the "roads flooded," "buildings flooded," and "value flooded" metrics. The erosion bars are an average of the percent changes within the "roads eroded," "buildings eroded," "buildings destroyed," and "value eroded" metrics. (2) The error bars denote a range in the percent changes between the metrics. (3) *Beach Accessibility* is the only metric interest that is not accounted for in this figure. (Color for this figure is available in the online version of this article.)

the will to utilize natural resource management and governance.

Remaining Questions

In the remaining interview questions, organizations were most concerned about the current and future impacts of natural physical hazards (erosion, tsunamis, flooding, earthquakes, and landslides), and built or man-made impacts (beach accessibility, aesthetic or scenic value of the coast, and construction of BPS). All 15 organizations expected to be engaged in adaptation policies and their challenges more often in the future due to state and federal requirements, intensified climate change, and more proactive federal, state, and local regulations.

DISCUSSION

In sum, statistical differences in metrics under alternative policy scenarios were dependent on the number and types of individual policies altered from the status quo. For example, the hybrid policy scenario contained completely different policies than those within the status quo, which aggressively moved buildings away from hazards. The hold the line policy scenario allowed the continued construction of BPS. The remaining individual policies failed to significantly lower the impacts of coastal hazards due to either an assumed resource limitation (due to the cost and frequency of beach nourishment) or a lack of future beachfront locations to restrict. Implementation of these alternative policy scenarios could quickly impact the landscape and make significant changes within the lifetime of an average mortgage (30 years).

Alternative policy scenarios were different than the status quo on average across the climate impact scenarios in three ways: (A) very helpful in lowering erosion with no statistically sustained impacts on flooding metrics (hold the line and laissez-faire) in the majority of climate impact scenarios, (B) moderately beneficial in lowering future erosion and flooding under all climate impact scenarios (Neskowin) with a slight increase in one erosion metric, or (C) greatly beneficial in lowering flooding impacts, but significantly damaging in terms of the erosional impacts in the majority of climate impact scenarios (realign and hybrid) (Figure 5). The sustained statistical benefits of policy scenarios B and C grew as the magnitude of SLR increased from low- to high-impact climate change scenarios, as opposed to the policy A scenarios, which became less beneficial. The percentages of beach accessibility were either the same or increased in comparison to the status quo under all policy and climate impact scenarios.

This mixed methods study illustrates a lack of convergence between the policies shown to have statistical benefit to the coastal community (by lowering the number of flooding and erosion events) and policies that are more easily implemented (Table 4). In this case, the policy scenario laissez-faire is most likely to decrease flooding and erosion; however, it is most difficult to implement under current laws and regulations.

Tillamook County organizations surmised that in addition to laws and regulations on the books, barriers to implementing adaptation policies were mostly due to the interests and motivations of poorly informed residents, as well as inadequate coordination between agencies and decision makers. Conversely, the most noted factors of success were top-down guidance with lower-level autonomy, and communicative and trustworthy community leadership. These insights point to clear opportunities for motivated government agencies and nongovernmental organizations at all levels to develop a middle

Table 2. *Summary of barriers to, components in, and Tillamook County–specific limitations on adaptation policy implementation (adapted from Dutra* et al.*, 2015). Only limitations mentioned five or more times were included. While only 10 interviews were held, multiple limitations may have been mentioned within each barrier/challenge category.*

Barrier/Challenge	Component	Tillamook County–Specific Limitation	No. of Mentions
Interests and motivation	Perceptions and assumptions	General opposition to any land-use restrictions/fear of regulatory takings/ governmental distrust	15
TOTAL Interests and motivation mentions			26
Information and knowledge	Limited knowledge/knowledge exchange	Lack of education/knowledge of policies, climate literacy, and coastal hazards	8
TOTAL Information and knowledge mentions			11
Organizational structures		No limitation had more than 3 mentions	
TOTAL Organizational structures mentions			11
Leadership		No limitation had more than 4 mentions	
TOTAL Power relations/leadership mentions			6
Resources		The only limitation had 4 mentions	
TOTAL Resources mentions			4
Other		The only limitation had 1 mention	
TOTAL Other mentions			1

ground where policies that lessen flooding and erosion match with current regulations and community sentiment.

CONCLUSIONS

Coastal communities are at high risk from coastal hazards, and local decision makers have historically lacked tools for developing adaptive capacity to reduce climate change–induced vulnerability. Local, county, and state governments continue to struggle with managing a dynamic and changing environment that is poorly matched with a slow-to-change governance structure. This paper describes an approach for informing decision making and increasing coastal community resilience to chronic coastal hazards by combining deep stakeholder engagement, a powerful alternative futures model (*Envision*), and robust evaluation of policy and climate change–induced coastal hazard scenarios.

Interested stakeholders in Tillamook County, Oregon, known as the Tillamook County Coastal Futures knowledge-to-action-network, worked to explore this lack of fit within their coastal system through the use of substantial stakeholder engagement and the *Envision* modeling platform. *Envision* allowed for the integration of spatially explicit natural and social landscape representations and projections of evolving coastal hazards under future climate change conditions with codeveloped coastal community adaptation policy scenarios of the coastal system to create and assess alternative future scenarios. Outcomes under five alternative policy scenarios (hold the line, laissez-faire, realign, Neskowin, and hybrid) were evaluated to determine if results (impacts to stakeholder-defined metrics of coastal flooding and erosion) were statistically different from the status quo and to characterize the feasibility of implementing the adaptation policies within Oregon's current state, county, and local regulatory environment.

Policy scenarios produced varying results over time and across the climate impact scenarios and stakeholder-identified

Table 3. *Summary of attributes, components, and Tillamook County–specific suggestions for success in adaptation policy implementation (adapted from Dutra* et al.*, 2015). Only suggestions mentioned five or more times were included. While only 10 interviews were held, multiple suggestions may have been mentioned within each attribute category.*

Attribute	Component	Tillamook County–Specific Suggestion	No. of Mentions
Leadership	Communication and collaboration	Knowledge and use of available resources (*i.e.* funding, best available science, university researchers) to support efforts	5
TOTAL Leadership mentions			15
Cross-sector cooperation and coordination	Autonomy and redundancy in authority and capability	Efforts on a local scale (*i.e.* emergency management and preparedness) with state and federal funding	6
TOTAL Cross-sector mentions			11
Effective integration of knowledge and insights		No suggestion had more than 4 mentions	
TOTAL Effective integration mentions			6
Human capacity and coordinated participation in decision making	Funding Organizational knowledge Bridging organizations	Knowledge and use of available resources (*i.e.* funding, best available science, university researchers) to support efforts	5
TOTAL Human capacity mentions			5
Learning approach to natural resource management and governance		No suggestions were mentioned under this attribute	
TOTAL Learning approach mentions			0
Other		No suggestion had more than 4 mentions	
TOTAL Other mentions			7

Table 4. *Comparison between beneficial policy scenarios and their implementation feasibility.*

Hold the Line	Laissez-Faire	Realign	Neskowin	Hybrid
Percentage of the eight metrics improved by the policy scenario				
21%	42%	38%	33%	38%
Likelihood policy scenario will be implemented (on a scale of zero to one, with zero being the easiest to implement)				
0.30	0.80	0.56	0.50	0.61

metrics. While no policy scenario achieved sustained statistical difference from the status quo in all eight metrics of interest, on average, the policy scenarios became statistically different from the status quo within the first third of the century, indicating the efficacy of implementation to limit future hazards within the time span of an average mortgage. In comparison to the status quo, the alternative policy scenarios were (A) very helpful in lowering erosion with no statistically sustained impacts on flooding metrics (hold the line and laissez-faire), (B) moderately beneficial in lowering future erosion and flooding (Neskowin) with a slight increase in one erosion metric, or (C) greatly beneficial in lowering flooding impacts, but significantly damaging in terms of the erosional effects (realign and hybrid).

Coastal decision makers consider not only the potential benefits, but also the possible limitations of implementing various policies within the current social and policy environment. This policy assessment identified policy scenarios that were relatively feasible (hold the line), moderately difficult (realign, Neskowin, and hybrid), and relatively impossible (laissez-faire) to implement. According to local organizations, social and organizational barriers to implementation were due to the mixed interests and motivations of the public and government agencies, and the limited exchange of information.

The assessments uncovered that the most beneficial policy scenario was in turn the most difficult to implement, illustrating the mismatch between policies that may lower flooding and erosion hazards along the coast and the existing governance environment in which they need to be implemented. However, many of the barriers identified in Tillamook County are analogous to those found in other natural resource management situations. As seen in Neskowin and elsewhere, lessening future climate change impacts will rely on leadership, and cross-sector cooperation and coordination to facilitate adaptation policy creation and, of critical importance, implementation. Communities may be further limited by a lack of stakeholder interest and fine-scale data, both important elements of Tillamook County's success so far. Government agencies must continue to strengthen connections with the public at large in order to consider the substantial economic and social impacts of policy implementation.

Even as many similar projects are underway around the world, the unique combination of significant stakeholder engagement, the transdisciplinary *Envision* framework, and the assessment of policy implementation feasibility goes steps further to provide applicable policy development tools to coastal community decision makers hoping to adapt to climate change along their coastline.

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