Exploring the Impacts of Climate and Policy Changes on Coastal Community Resilience: Simulating Alternative Future Scenarios

by

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Abstract: Coupled models of coastal hazards, ecosystems, socioeconomics, and landscape management in conjunction with alternative scenario analysis provide tools that can allow decision-makers to explore effects of policy decisions under uncertain futures. Here, we describe the development and assessment of a set of model-based alternative future scenarios examining climate and population driven landscape dynamics for a coastal region in the U.S. Pacific Northwest. These scenarios incorporated coupled spatiotemporal models of climate and coastal hazards, population and development, and policy and assessed a variety of landscape metrics for each scenario. Coastal flooding and erosion were probabilistically simulated using 99 future 95-year climate scenarios. Five policy scenarios were iteratively co-developed by researchers and stakeholders in Tillamook County, Oregon. Results suggest that both climate change and management decisions have a significant impact across the landscape, and can potentially impact geographic regions at different magnitudes and timescales.

Additional Keywords: climate change adaptation planning, coastal community resilience, coastal flooding, coastal hazards, Envision, Tillamook County, OR

1. Introduction

With the continuous influx of populations to coastal regions, human stresses on resources and ecosystems coincide with climate change, resulting in uncertain and potentially less habitable shorelines worldwide (Neumann et al., 2015). The coastal U.S. Pacific Northwest faces an increased risk of hazards as a result of sea-level rise (SLR) and changing storminess patterns (Ruggiero et al., 2010; Allan and Komar, 2006). However, future trends in SLR, storm frequency, and wave climate attributed to global climate change are difficult to accurately predict, particularly at local scales. SLR is highly spatially and temporally variable, and while there is a documented acceleration of mean global SLR, local, regional, and global processes contribute a high degree of uncertainty (e.g., Kopp et al., 2017; NRC, 2012; Sallenger et al., 2012; Yin et al., 2010). Additionally, downscaled predictions of future wave heights , storm intensity and frequency, and patterns of El Niño Southern Oscillation (ENSO) have variable projections by the end of the century either ameliorating or exacerbating potential coastal flooding and erosion (Cai et al., 2014; Hemer et al., 2013; Wang et al., 2014, Erikson et al., 2015).

The inherent geographic variability in climate impacts emphasizes the need for place-based approaches to climate vulnerability analysis and adaptation planning that also take into account the values of local stakeholders (e.g., Kelly and Adger, 2000; Moser et al., 2012; Turner et al., 2003). Community exposure to coastal change hazards varies depending upon how communities respond and adapt to risk as well as to how human population growth and development drive the evolution of the coastal system. As such, it is critical that community planners understand the impacts of policy decisions when developing adaptation strategies to address these emerging challenges in ways that are both cost-effective and sustainable into the future. Examples of solutions that can potentially prevent community exposure to coastal hazards include (a) hard and soft engineering solutions (e.g. rip-rap revetments, sea walls, or beach nourishment); (b) nonstructural measures that accommodate coastal risks while continuing coastal occupancy and land use (e.g., flood insurance, stricter building and zoning codes, and elevating structures); or

(c) relocation away from coastal hazard zones (e.g., planned retreat using construction setbacks, buy-outs, and reactive relocation from the shoreline; Klein et al., 2001). Understanding the consequences of such policies is essential to developing adaptive capacity, or the ability to sustain quality of life, within coastal communities (Gallopín, 2006; Smit and Wandel, 2006).

To evaluate the impact of policy decisions under uncertain future climate conditions, an approach is needed that marries the predictive and dynamic capabilities of simulation models with a scenario methodology that incorporates stakeholder values and co-developed adaptation strategies (Keeler et al., 2015, Karvetski et al., 2011). Policy and climate scenarios have recently been combined within modeling platforms to assess climate change impacts and vulnerabilities across different sectors (e.g. Le et al., 2010; McNamara and Keeler, 2013; Bolte et al., 2007) and these platforms have emerged as powerful tools in integrated assessment and policy analysis within the context of climate change because they account for a range of uncertainty in complex dynamic systems (Berkhout et al., 2002). Modeling alternative pathways of plausible futures can estimate the magnitude and extent of future climate change, the associated potential impacts on physical, natural, and human systems, the costs and possible effectiveness of mitigation and adaptation policies, the interactions among and trade-offs between climate change impacts and adaptation policies, and the relationships between climate change and socioeconomic development (Berkhout et al., 2013; Mokrech et al., 2012; Moss et al., 2010; Nicholls et al., 2008; van Vuuren et al., 2011). Simulations of alternative futures can ultimately help identify the most important interactions across spatial and temporal scales, leading to improved understanding of the structure and behavior of these systems by researchers and stakeholders alike.

Here we present a transferrable methodology for development and evaluation of alternative futures with respect to coastal flooding and erosion in Tillamook County, Oregon within a spatially explicit, multi-paradigm model integration framework. First, the background establishes the historic climatologic and socioeconomic baseline in Tillamook County followed by a discussion of the modeling platform used, *Envision*, and the development of a suite of probabilistic climate change scenarios that reflect various assumptions regarding SLR, wave height, and major ENSO occurrences and their impact on future total water levels (TWLs). In addition, the methodology details the five policy scenarios that were developed iteratively with a group of stakeholders to capture a range of landscape management options. Finally, the resulting alternative futures are evaluated using a suite of landscape metrics, and the benefits and drawbacks of various adaptation strategies under a range of climate scenarios are explored along with an analysis of the model sensitivity to parameterization of the human system.

2. Coastal Tillamook County, Oregon

Roughly 23 percent of Tillamook County's approximately 25,320 permanent residents live within a half mile of the Pacific Ocean (Figure 1, U.S. Census Bureau, 2014). The 104 kilometer (including the estuarine shoreline) coastline also draws visitors and non-permanent residents alike. Coastal geomorphology varies from sandy, dune backed beaches, which compose the majority of the shoreline (~55%), to cliffs (~21%), to bluff-backed beaches (~11%), to sandy beaches backed by rip rap revetments (~ 8%), and cobble and boulder beaches adjacent to headlands (less than 5%). Headlands restrict alongshore sediment transport between four littoral cells, which are further divided by estuaries (Figure 1).

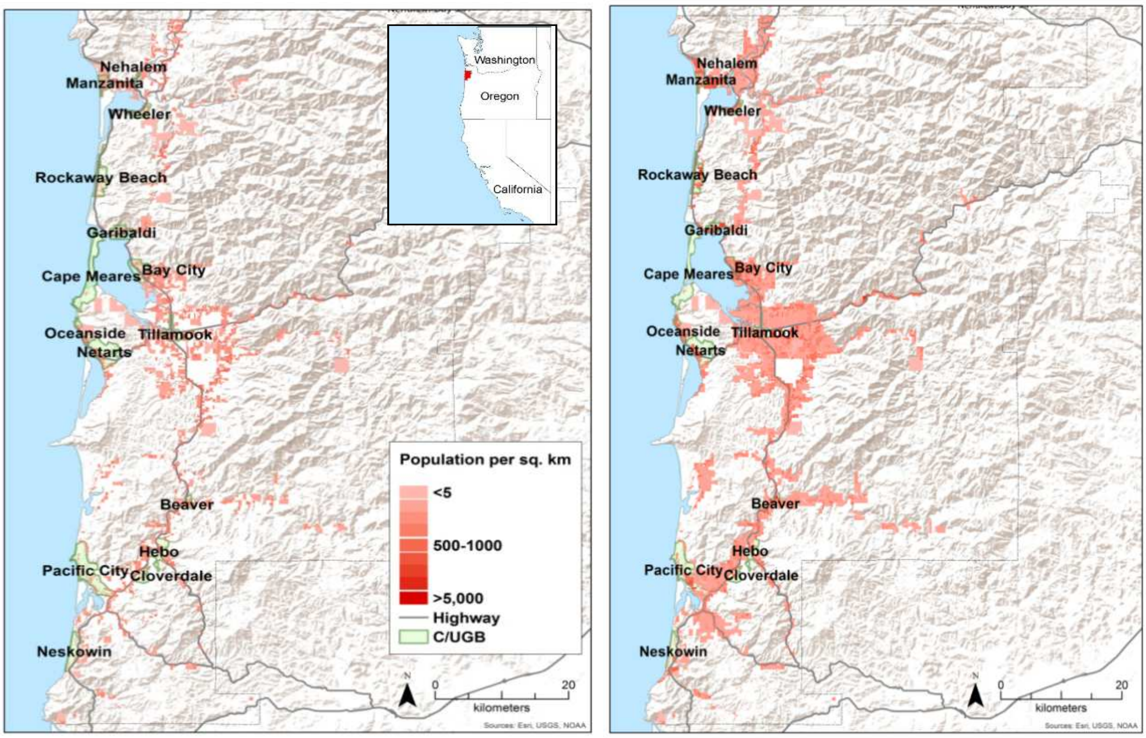

Figure 1: Tillamook County population in 2010 (left) and projected population under a *Status Quo* policy scenario (i.e., no change in current policies) in 2100 (right)

An increase in coastal hazards over the past few decades within Tillamook County can be attributed to three main climatological drivers; SLR, increases in wave heights (related to winter storms), and the frequency of major ENSO events. Komar et al. (2011) found rates of relative SLR of approximately 1.3 mm per year along the central to northern Oregon Coast between 1980 and 2010. Further, the Pacific Northwest is exposed to extreme extratropical storms, with winter waves regularly reaching heights in excess of 8 meters (Allan and Komar, 2006). Ruggiero et al. (2010) found a trend of increasing wave heights along the Oregon Coast, with the annual mean increasing at a rate of 1.5 cm per year, the winter mean increasing at a rate of 2.3 cm per year, and annual maximum wave heights increasing at a rate of 9.5 cm per year over a three-decade period. In addition, recent major El Niño events (i.e. 1997/1998, 2009/2010) resulted in severe flooding and erosion in the region (Sallenger et al., 2002). At present, over 65% of the Tillamook County outer coastline is erosional with approximately 40% of the coast eroding at rates exceeding one meter per year (Ruggiero, et al., 2013).

3. Envision Framework

Envision (Bolte et al., 2007) is a multi-paradigm model integration platform which couples landscape process models with socioeconomic drivers and management strategies to explore trajectories of change through time via a variety of metrics (Figure). *Envision* has been used to characterize floodplain trajectories (Hulse et al., 2009), land use planning and impacts of urban expansion (Guzy et al., 2008, Wu et al., 2015), wildfire–land management (Yospin et al., 2015; Koch et al., 2012, Spies et al., 2017), land use/water/climate interactions (Inouye et al., 2017; Hulse et al. 2016; Han et al., 2017; Turner et al., 2016) and other coupled human/natural systems. *Envision's* support for mixed simulations incorporating conventional models and decision-making "actors" allows exploring the complexity of landscape patterns that result when decision-making entities and their policies are included as part of evolving landscapes.

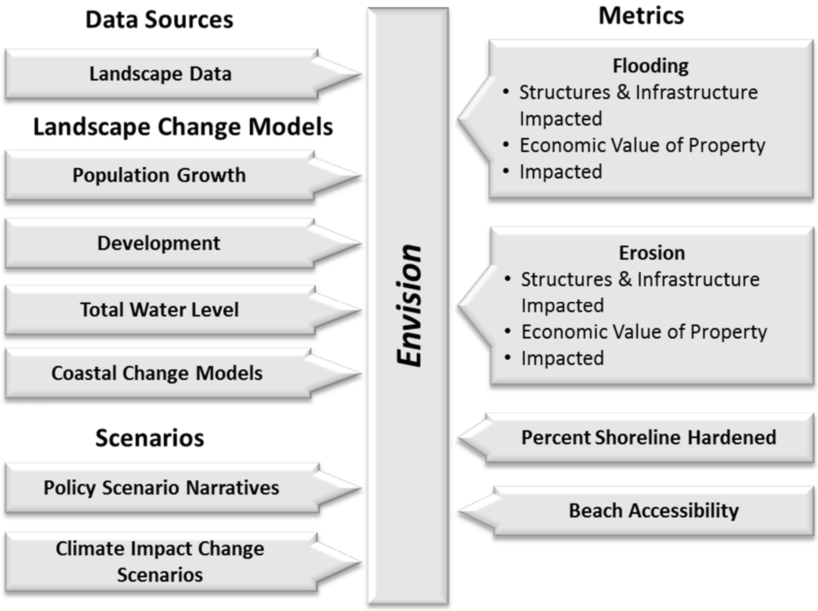

Figure 2: Envision inputs, landscape change models, and evaluative models specific to the modeling of coastal hazards in Tillamook County, Oregon.

Alternative futures analysis within *Envision* involves three primary aspects: 1) dataset development, 2) model development and integration, and 3) policy scenario development. Dataset development occurs in conjunction with stakeholder engagement subsequent to the determination of relevant evaluative metrics. All datasets must be spatially explicit (e.g., census tracks, geomorphologic parameters). *Envision* enables spatial-temporal simulation of landscape change through the synchronization of multiple submodels.

Envision includes a multi-agent modeling subsystem to represent human decisions on the landscape. A set of actors operate across the landscape by selecting and applying policies in response to landscape signals and other factors influencing their decision-making behavior. In *Envision*, actors can be based on individuals, collections of individuals, or abstractions with no real world counterpart. In the case of our application of *Envision* to Tillamook County, actors represent the collection of individuals associated with county-defined tax lots. The application of a policy by an actor results in changes of landscape attributes. Policies (decision rules) contain information about site attributes defining where the policy can be considered and outcomes that the policy is intended to accomplish.

3.1 Envision Simulation

During simulation, *Envision* generates a set of both spatially detailed and spatially aggregated landscape evaluators reflecting scenario outcomes for a variety of metrics, most notably development/land-use patterns, shoreline modifications, population projections, and impacts to the landscape by coastal hazards. These landscape metrics indirectly introduce feedbacks into the system by quantifying the actor or policy's impact on the landscape. The sections below describe (1) how Tillamook County was represented geospatially, (2) the submodels used to simulate coastal hazards, population growth, and development, and (3) the development of climate change and policy scenarios.

3.2 Geospatial Representation of the Landscape

A landscape in *Envision* consists of a set of spatial containers or polygons termed integrated decision units (IDUs) that specify the resolution at which processes and actors can operate on the landscape. For this study, the 2,900 km^2 study area of Tillamook County was divided into approximately 130,000 IDUs. Areas of the IDUs range from less than 50 square meters to greater than 10 square kilometers. The IDUs were formed through the intersection of multiple geometric layers representing baseline data. The baseline geometry for the IDU layer were county defined tax lots with underlying information including ownership, zoning, and presence of a dwelling or building. Each IDU has a unique set of attributes relevant to the landscape and evaluative models. Taxlots near the shoreline were further subdivided using a 100 m alongshore by 10 m cross shore grid to more accurately resolve coastal flooding and erosion hazards.

3.3 Submodels

Submodels, or "plug-ins", periodically change the underlying landscape, reflecting biophysical processes that occur independently of human action. The modular architecture of *Envision* allows for the inclusion of any number of compliant submodels. The submodels used within this case study in coastal Tillamook County, OR are described below. 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 use of more sophisticated models when warranted.

3.3.1 Probabilistic Simulation of Total Water Levels

Probabilistic simulations of total water levels (TWLs) were used to derive coastal flooding and erosion submodels along the outer coast. TWLs are calculated as a linear superposition of the tide, non-tidal residual, and wave induced runup (Allan and Komar, 2006; Ruggiero, 2013; Ruggiero et al., 2010).

$$TWL = MSL + \eta_A + \eta_{NTR} + R \quad \textbf{(1)}$$

where MSL is the mean sea level, η_A is the deterministic astronomical tide, and η_{NTR} is the nontidal residual generated by a range of physical processes including wind setup, barometric surge, and low frequency water level anomalies. *R*, the 2% exceedance level of the vertical extent of wave runup on a beach or structure above some datum, was calculated using the empirical model of Stockdon et al., (2006) on dune backed sandy beaches, and the modified TAW (Technical Advisory Committee for Water Retaining Structures, van der Meer, 2002, Allan et al., 2015) approach on beaches backed by bluffs, cobble berms, and backshore protection structures (BPS, i.e., riprap revetments).

Using the total water level full simulation model (TWL-FSM) developed by Serafin and Ruggiero (2014), probabilistic time series of wave height, wave period, wave direction, MSL, η_A and η_{NTR} allowed for the incorporation of variability and non-stationarity within climate change scenarios. These TWL parameters were generated for a deep-water location not affected by shoaling or refraction processes. As such, it was necessary to then propagate the waves toward the nearshore using regional bathymetry. Because the numerical transformation of waves is computationally expensive over a large study region, lookup tables were developed to relate offshore (deep water) triplets of significant wave height (SWH), peak period (T_p), and mean wave direction (MWD) to their nearshore (20 m water depth) equivalents using radial basis functions (Camus et al., 2011). The wave climatology was discretized into representative wave conditions which were transformed to the nearshore (García-Medina et al., 2013) using stationary model runs of SWAN (Booij et al., 1999). This allows for any combination of a deep water triplet's nearshore equivalent to be interpolated from the results of the SWAN model runs. Wave runup parameterization (Stockdon et al., 2006, van der Meer, 2002) relies on the deep water equivalent SWH and T_p as inputs, so transformed waves were linearly back shoaled from the 20 m contour to deep water. These transformed deep water waves were ultimately used to generate TWL conditions in combination with 100m (alongshore) resolution geomorphology including backshore beach slope (defined as the slope between the MHW shoreline contour and the dune toe), dune crest, and dune toe which were extracted from a combination of 2009 lidar data from Oregon Department of Geology and Mineral Industries (DOGAMI) and 2011 lidar data from U.S. Army Corps of Engineers using techniques developed by Mull and Ruggiero (2014).

3.3.2 Coastal Flooding

To reduce computational complexity, flooding within *Envision* was calculated only for the maximum yearly TWL event using a bathtub-type inundation model which considers only two variables: the inundation level and ground elevation (Schmid et al., 2014). The coastal hazards submodel allows for selection of alongshore variable yearly maxima such that different storms throughout the year may produce the maximum TWL event for each alongshore location depending upon local geomorphic and climatic conditions. Because of the simplicity of the bathtub model, TWLs at inlets were reduced to reflect a combination of non-tidal residual and tide only while the full TWL was used for the remainder of the coastline. Flooding occurred only if the dune or BPS crest was overtopped by the TWL. To determine pathways of flooding in the backshore, hydraulic connectivity between individual IDUs was determined using a 1 m resolution Digital Elevation Model (DEM).

3.3.3 Coastal Erosion

Coastal retreat is evaluated following Baron et al., (2014) as

$$\text{Coastal Erosion} = (CCR_{SB} + CCR_{Climate}) * \mathrm{T} + CC_{Event} \tag{2}$$

where CCR_{SB} is the long-term (interannual- to decadal-scale) coastal change rate, $CCR_{climate}$ is the coastal change rate associated with SLR, T is time in years, and CC_{Event} is the event-based erosion associated with the maximum yearly TWL. Within the model, erosion was restricted to dune-backed beaches as failure of BPS and bluff/cliff erosion was not modeled.

Extrapolating an end-point shoreline change rate (1967 – 2002) was used to capture continued erosion associated with the regional sediment budget (CCR_{SB} , Ruggiero et al., 2013). The influence of SLR on erosion was characterized using the Bruun Rule (1962). Given a yearly rise in SLR, the yearly landward shoreline retreat was found as follows

$$CCR_{Climate} = \frac{L}{B + h_c} SLR = \frac{SLR}{tan\beta_{sf}} \tag{3}$$

where L is the cross shore distance to the water depth h_c, B is the elevation of a backshore feature (BPS or dune), and $\tan\beta_{sf}$ is the shoreface slope computed between mean high water line (MHW, 2.1 meter contour relative to NAVD88) and h_c, taken here to be the 25 m isobath. On dune-backed beaches, the shoreface slope remained static through time as the dune eroded landward while the dune toe elevation rose at the rate of SLR. On beaches backed by BPS, the beach was assumed to narrow at the rate of the total chronic erosion ($CCR_{SB} + CCR_{Climate}$).

Beaches were further narrowed in the process of maintaining (i.e. raising to accommodate higher TWLs) and constructing BPS structures at a 2:1 slope.

Coastal retreat during large winter storm events or periods of elevated water levels was also modeled in the form of wave-induced foredune erosion, in which the magnitude of erosion depends on the elevation of the TWL relative to the toe of the foredune (Ruggiero et al., 2001; Sallenger, 2000; Stockdon et al., 2006). Based on the model suitability study of Mull and Ruggiero (2014), a modification of the foredune erosion model presented by Kriebel and Dean (1993) was implemented within the coastal hazards submodel. The event-scale dune erosion model assumes that the volume of sediment eroded from the foredune during a storm is deposited in the nearshore as the equilibrium profile shifts as follows

$$CC_{Event} = \frac{T_D}{T_S}\left(\frac{(TWL_{\max yearly} - MHW)\left(x_b - \frac{h_b}{tan\beta_f}\right)}{dhigh - MHW + h_b - (TWL_{\max yearly} - MHW)/2}\right) \quad \textbf{(4)}$$

where T_D is the storm duration, T_S is the erosion response time scale, x_b is the surf zone width measured from the MHW position using an equilibrium profile (Dean, 1991), h_b is the breaking-wave water depth relative to MHW, $tan\beta_f$ is the beach slope, and $dhigh$ is the elevation of the dune crest. Calculating CC_{Event} for a particular storm required scaling the erosion response using a ratio of the erosion response time scale (T_S) to the storm duration (T_D). T_S is theoretically dependent upon the ability of sediment to withstand erosive wave forces and was calculated as a function of h_b and $dhigh$ (Kriebel and Dean, 1993). A mean storm event duration (approximately 10 hours in which the TWL is elevated above MHW) was used for the entire study region, calculated using an alongshore averaged value using the 30-year event record developed by Serafin and Ruggiero (2014).

3.3.4 Population Growth

While the allocation of people and development varied based upon policies articulated within policy scenarios, the mechanisms for that allocation remained constant across all alternative future scenarios. Within *Envision*, two models were used to simulate the spatial pattern of population growth and subsequent development processes across the landscape of Tillamook County.

An *Envision* submodel, *Target (Envision* Developer's Manual, 2015), was used to allocate new population growth at the IDU level. Specific data required for this analysis included tax lot coverage, zoning data and maximum capacities for each zone type, census data, and information regarding growth rates. *Target* allocates population at some overall study wide growth rate onto the polygonal IDU landscape through the creation and examination of two surfaces: 1) a current population density surface, and 2) a population capacity surface. The population capacity surface represents build-out population density of the IDU based on zoning class. The allocation of growth involves an IDU-by-IDU evaluation of existing population and of the capacity for new population. New population is spatially allocated proportionally to the difference between the existing density and the capacity surface, resulting in the model moving the existing density surface towards the capacity surface. This function was modified by introducing weighted preference factors (e.g., a preference to locate near the coastline) into the allocations. These preference factors modify the differences between the existing density surface and capacity surface based on underlying IDU values, defined via a spatial query associated with the preference, and were estimated based on past growth patterns in the study area.

In lieu of IDU-level population data, initial IDU population density was estimated from the 2010 census at the block-group level. A single projection of population growth from the Oregon Office of Economic Analysis through 2050 was used across all policy scenarios. Subsequent to 2050, a constant population growth rate was used allocating a total of approximately 12,000 new residents into the county by 2100 (Oregon Office of Economic Analysis, 2013). Because no spatially explicit projections of population growth exist for the Tillamook County study area, urban growth areas and community growth areas were assumed to maintain a constant fraction of the county-wide population through 2100 while still allowing geographic preferences between policy scenarios.

3.3.5 Development

New development was allocated to the landscape based on the population growth rate in a separate *Envision* submodel, *Developer (Envision* Developer's Manual, 2015). The number of people per dwelling unit varied by town or city and also by distance from the coast. Many coastal dwellings are owned as non-primary homes; therefore the number of people per dwelling unit is much lower than the number of people per dwelling unit in areas further from the coast. For each pre-defined area, new population growth determines the number of new dwelli+ng units required, and within each IDU, the dwelling unit capacity was based on the population density. At each time step, this capacity was used to generate a sorted list based on the greatest discrepancy between population density and number of existing dwelling units. Dwelling units were allocated until the entire new population for that time step was accommodated. Finally, a Hedonic pricing model (e.g. Bin et al., 2008) was used to determine the value of new development as follows

$$Assessed\ Value\ (\$) = f\begin{pmatrix}\text{lot size, distance to shoreline, presence of BPS, distance to major highway,} \\ \text{number of buildings, geographic location (within growth boundaries)}\end{pmatrix} \quad \mathbf{(5)}$$

3.4 Scenario Development

3.4.1 Climate Change Impact Scenarios

Probabilistic TWL simulations combining variations of SLR, wave climate, and the probability of occurrence of major El Niño events from the year 2005 through 2099 accounted for uncertainty in climate projections and served as climate impact scenarios. First, projections from the *National Research Council's Sea Level Rise for the Coasts of California, Oregon, and Washington (2012)*, were used to define three SLR scenarios; low, medium, and high (Figure 1). The NRC (2012) report was used as it was well known to stakeholders during the project and was considered appropriate since it contains SLR projections relevant for the US west coast. While specific to Oregon and Washington, bounds on the SLR projections still maintained a high range of variability as they included a combination of regional steric and ocean dynamics, cryosphere and fingerprinting effects, and vertical land motion.

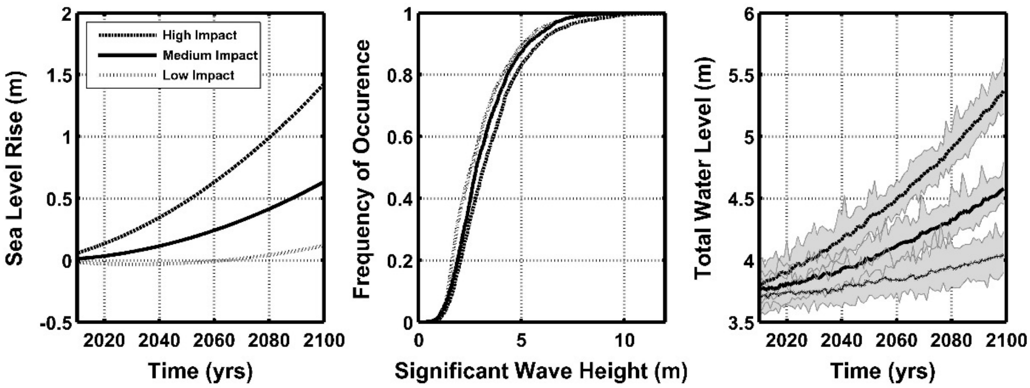

Figure 3: Three SLR (high, medium, and low) scenarios from NRC (left), the shift in wave climate from early to late century (center), and the mean yearly TWL. The solid line in the distribution figure (right) represents a "present-day" SWH distribution. The dotted line to the right represents an increase to the present-day SWH distribution, while the dotted line to the left represents a decrease in the present-day SWH distribution by 2100. Bounds around the TWL represent the max and min of the yearly average.

Next, projected changes in the wave climate were based on significant wave height (SWH) distributions developed from the variability of statistically and dynamically downscaled projected global climate model estimates for the Northeast Pacific Ocean (Hemer et al., 2013; Wang et al., 2014) . To account for the range in variability in the downscaled data, the wave climate was allowed to increase or decrease across the various SLR scenarios (Figure 1).

Finally, water levels and wave heights are also affected by major El Niño events, which have been associated with severe flooding and erosion in the U.S. Pacific Northwest (Komar, 1998, Kaminsky et al. 1998, Barnard et al., 2017). Due to the uncertainty surrounding the changing occurrence of storms, the frequency of major ENSO events was allowed to vary continuously between half of present day frequency (~once per two decades) and double present day frequency. These combinations of three SLR scenarios, wave climate variability, and ENSO frequency projections were used to capture the inherent variability of the physical drivers. Thirty-three probabilistic TWL simulations for each high, medium, and low impact climate change scenario, resulted in a total of 99 different 95-year projections of daily maximum TWLs.

3.4.2 Policy Scenarios

The alternative futuring process allowed for feedback and learning opportunities at several levels. The first came through the utilization of the modeling framework, *Envision*, as described above. A second opportunity arose when the model design or results were used to interact with stakeholders to gain information with respect to decision-making across the landscape. To accomplish the latter, a group of local stakeholders, including representatives from state legislature, community advisory committees, city managers and mayors, county commissioners, and property owners, among others, were consulted to identify possible policy scenario narratives to be represented within *Envision*. This participatory modeling approach fostered an environment of ownership and understanding amongst both researchers and the stakeholder community, and ensured that the co-produced scenarios modeled were representative of a broad range of policy options. More details describing the stakeholder interaction can be found in Lipiec et al., (2018).

Policies were developed based on discussions with stakeholders and reflect several categories, including shoreline modifications and development restrictions. Each policy was modeled with as specific set of triggers, or assumptions. Some of these triggers were based upon historic evidence while others that lacked concrete examples in the Pacific Northwest were generated and validated through collaboration with the stakeholders or a literature review. For example, in determining when buildings must be relocated within or removed entirely from parcels in response to hazards, current policy language states that the building must require repairs equal to half of the value of the property (i.e., a significant repairs requirement). Because the current version of the coastal hazards submodel computes flooding as a binary state and does not simulate flow depths and velocities, the aforementioned threshold was impossible to capture. In this particular case, repetitive impact to buildings by coastal hazards provided a proxy for significant damage because the size of the study area precluded the use of more computationally expensive physics-based flooding and erosion models.

Sets of individual policies made up a total of four initial policy scenario narratives (*Status Quo*, *Hold the Line*, *ReAlign*, and *Laissez-Faire*) in order for stakeholders to weigh tradeoffs and evaluate differences between scenarios (Table 1). Each policy scenario narrative dictated how actors managed the landscape, both in terms of how and where population growth and development were allocated, and how people and resources were protected from coastal hazards. A fifth policy scenario, *Hybrid*, was generated through a ranking process in which stakeholders voted for preferred policies and scenarios based on initial results from the four initial policy scenarios. Each of the five policy scenarios was crossed with the 99 climate change impact scenarios, resulting in 495 alternatives futures through which landscape metrics were evaluated to assess the relative effectiveness of management options.

Table 1: Five policy scenarios co-developed with stakeholders and incorporated into the model.

Policy Scenario Narrative	Policies
Status Quo: **Continuation of present day policies.**	• Determine urban/community growth boundaries (U/CGB) in accordance with present-day policy. • Maintain current BPS and allow more BPS to be built on eligible lots.
Hold the Line: **Policies are implemented that involve resisting environmental change in order to preserve existing infrastructure and human activities**	• Determine U/CGB in accordance with present-day policy. • Maintain current BPS and allow more BPS to be built on eligible lots. • Add beach nourishment where beach access in front of BPS has been lost. • Construct new buildings or developments only on lots eligible for BPS construction • Construct new buildings above the Federal Emergency Management Agency's (FEMA) Base Flood Elevation (BFE) plus an additional 3ft and in the safest site of each respective lot.
ReAlign: **Policies are implemented that involve shifting development to suit the changing environment.**	• Determine U/CGB in accordance with the present-day policy but with prevention of new development within coastal hazard zones. • Prohibit construction of BPS on additional properties, regardless of Goal 18 eligibility, but maintain previously constructed BPS. • Construct new buildings above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot. • Remove buildings impacted repetitively by coastal hazard from within the hazard zone and establish conservation easements. • Inventory lots located outside of the coastal hazard zones and re-zone to permit future higher density development within the U/CGB.
Laissez-Faire: **Current policies (state and county) are relaxed such that development trumps the protection of coastal resources, public rights, recreational use, beach access, and scenic views.**	•Permit increased proportion of development outside the U/CGB. •Eliminate BPS construction requirements.
Hybrid: **Policies are implemented in accordance with the preferences established by the Tillamook County stakeholders that involve shifting development to suit the changing environment.**	• Determine U/CGB in accordance with the present-day policy but with development restrictions within coastal hazard zones. • Prohibit construction of BPS on additional properties, regardless of Goal 18 eligibility, but maintain previously constructed BPS. • Construct new buildings above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot. • Remove buildings impacted repetitively by coastal hazard from within the shoreline and establish conservation easements. • Inventory lots located outside of the coastal hazard zones and re-zone to permit future higher density development within the U/CGB. •Require movement of buildings frequently impacted by coastal hazards to a location

	above the FEMA BFE plus an additional 3ft and in the safest site of each respective lot. If the building was again impacted by coastal hazards, remove it from within the hazard zone and establish conservation easements.

4. Evaluating Alternative Futures with Respect to Landscape Metrics

While over 100 variables were tracked during simulations, stakeholders identified a core set of metrics for the exploration of alternative futures within *Envision* (Lipiec et al., 2018*)*. In general, the most important metrics were related to 1) growth and development, 2) exposure to coastal hazards and mitigation techniques, 3) public good. The following sections explore example metrics in each of these three categories as well as the relative difference in hazard impacts between individual communities.

4.1 Metrics related to growth and development

Because many of the adaptation and land use management policies employed alter development patterns on the landscape, growth and development were compared across the five different scenarios. Figure 4 illustrates the simulated trends involving development within the coastal hazard zone. None of the five policy scenarios allocated more than 500 additional buildings within a coastal hazard zone determined by the Oregon Department of Geology and Mineral Industries (Allan and Priest, 2001), with the *Laissez-Faire* policy scenario allocating the greatest number due to the relaxation of growth boundaries and increased likelihood of development closer to the shoreline. Because the projected county-wide growth rate was moderate (0.39%-0.78% per year), no community growth boundaries were filled to capacity. In the *Hold the Line* policy scenario, new growth in the hazard zone was limited primarily by a policy which permits construction only on the safest site within a parcel and secondarily by a policy which permits development only on beachfront properties eligible to construct BPS (Table 1). The bounds of climate variability (shaded areas within Figure 4) were largest for the policy scenarios (*ReAlign* and *Hybrid*) which remove buildings and population from the coastal hazard zone through an easement process. Up to 1,800 buildings were relocated to safer areas outside the hazard zone in the *ReAlign* policy scenario under the mean of all high impact probabilistic climate (TWL) scenarios (Figure 4, right). Approximately 500 fewer buildings are converted to easements in the mean low impact climate scenario. In the *Hybrid* policy scenario, in which buildings are first relocated to the safest site of the parcel and then removed from the hazard zone if hazard exposure persists, fewer properties were transitioned into easements than within the *ReAlign* policy scenario. These development patterns altered subsequent community exposure to coastal hazards.

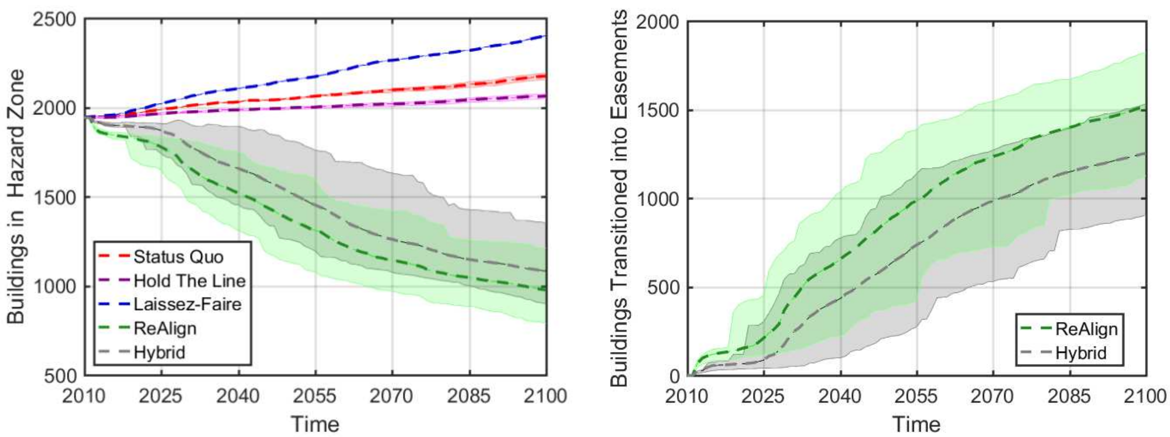

Figure 4: County-wide number of buildings located within the coastal hazard zone (left) and number of buildings relocated out of the coastal hazard zone through an easement process (right). Easements only occur under the ReAlign and Hybrid policy scenarios. Dashed lines indicate the mean of the medium impact climate scenarios. Shading indicates the range of the mean of the low and high impact climate scenarios.

4.2 Metrics related to hazard exposure

Metrics related to hazard exposure provided insight regarding (1) when homeowners will need BPS to protect their property, (2) how property will be impacted by coastal flooding and erosion hazards, and (3) how costs of protecting property change over time. Within the five policy scenarios, BPS and beach nourishment were the only two coastal engineering mechanisms (hard and soft) considered for the protection of backshore development. To protect property from erosion, most beachfront property owners would need to armor their properties prior to 2040 according to simulation results (Figure 5).

Figure 5. BPS constructed through time in a medium impact climate scenario under the *Status Quo* policy scenario in Rockaway Beach

More BPS were constructed in the *Laissez-Faire* policy scenario than in the other policy scenarios as restrictions related to BPS construction permitting were eliminated (Figure 6). In the *ReAlign* and *Hybrid* policy scenarios, further armoring of the shoreline was prevented, thus the percent of shoreline hardened was constant through time. In Rockaway Beach, a maximum of ~80% of the shoreline was hardened as the community was predominately developed by the end of the century (Figure 6, left). County-wide however, no policy scenario armored more than 30% of the entire shoreline as population along most of the coast was still relatively sparse by 2100 (Figure 6, right). Variability due to climate scenarios altered the extent of armored coastline by no more than 10%.

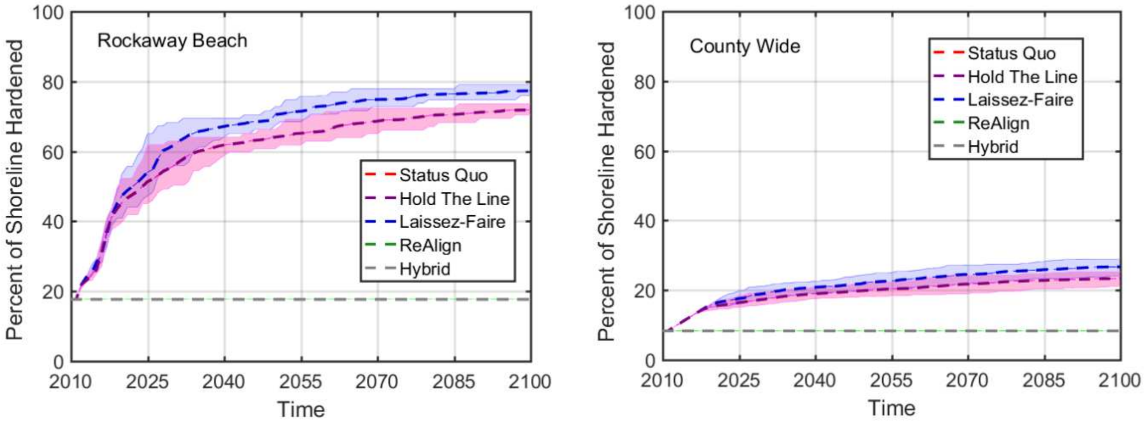

Figure 6. Percent of shoreline hardened through time in the Rockaway Beach littoral subcell (left) and in all of Tillamook County (right). Restrictions to BPS construction in *Hold the Line* and *Status Quo* are similar, so the extent of shoreline hardened in both of these policy scenarios is equal. Similarly, *ReAlign* and *Hybrid* policy scenarios allow no further armoring of the beach and thus overlap in the figure above. Dashed lines indicate the mean of the medium impact climate scenarios. Shading indicates the mean of the low and high impact climate scenarios.

As a result of shoreline armoring, the number of properties exposed to event-based erosion through time was reduced in three of the five policy scenarios (Figure 7, right). The sharp reduction in the number of buildings impacted by event-based erosion is due to either the construction of BPS or the formation of easements early in the century. The *Laissez-Faire* policy scenario resulted in the fewest number of buildings impacted by erosion (event-based or long-term) as property owners constructed BPS regardless of current eligibility status. Variability in the number of buildings impacted by event based erosion was minimal between climate impact scenarios. The lack of BPS construction in the *ReAlign* and *Hybrid* policy scenarios resulted in greater impacts to buildings by erosion and greater variability with respect to climate scenarios. In addition to the buildings exposed to event based erosion, buildings were removed by the long-term shoreline change rate (due to both sea level rise and sediment budget factors) once the toe of the dune moved landward of the building (Figure 7, left). Under policy scenarios in which BPS construction was permitted but limited based on current Oregon laws, up to 45 buildings were lost due to long-term shoreline change. Under the *ReAlign* and *Hybrid* policy scenarios, buildings were removed via easements and thus were not lost due to chronic erosion.

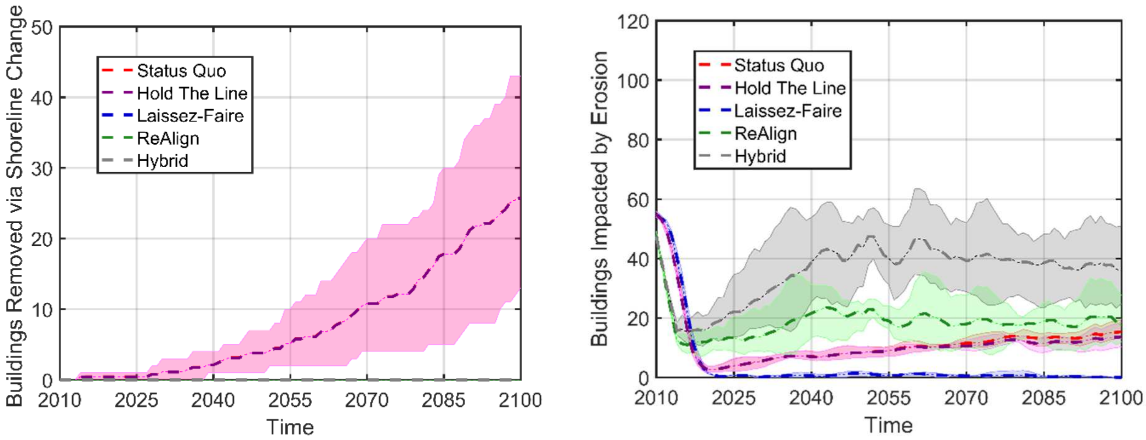

Figure 7: The cumulative number of buildings removed from the landscape by long term shoreline change (left) and the average number of buildings impacted annually by event based erosion (right). Dashed lines indicate the mean of the medium impact climate scenarios. Shading indicates the mean of the low and high impact climate scenarios. Scenarios that appear in the legend but not in the figure indicate zero values for the associated metrics.

The value of property impacted by flooding was assessed under both low and high impact climate scenarios (Figure 8). Near the end of the century, there was greater variability in the low climate impact scenario than in the high impact scenario, although in general more property was impacted by flooding in the high impact climate scenario, and is more than doubled under the *Laissez-Faire* policy scenario. The decrease in variability within the high SLR scenario was due to the exceedance of a flooding threshold by approximately mid-century, after which the combined effects of SLR and geomorphologic change resulted in the frequent-to-persistent inundation of property within the coastal hazard zone. The increase of property impacted by flooding during the first half of the century was in response to the construction and maintenance of BPS. Because BPS prevented any landward migration of the dune, the long term erosion rate due to both sediment budget factors and to SLR causes the beach to narrow, thus increasing TWLs. While homeowners were able to build up BPS in response to rising TWLs, they were limited by the elevation of the property and a requirement to maintain a viable viewshed. In addition, raising the elevation of the structure crest forced the extension of the structure horizontally, further narrowing the beach. Thus, the presence of BPS increased beach slope, often increasing exposure to coastal flooding. In this analysis, BPS were predominately unsuccessful at reducing flooding hazards within Tillamook County. The highest value of property impacted by flooding occurred under the *Laissez-Faire* policy scenario, both because BPS construction was permitted without restriction and because the rate of new development near the shoreline was elevated. In the *ReAlign* and *Hybrid* policy scenarios, fewer flooding impacts occurred by 2100 compared to the other policy scenarios due to both the relocation of people and development away from coastal hazard zones and the limitation of further BPS construction. Variability within these two policy scenarios (*ReAlign* and *Hybrid)* with respect to climate was also the smallest towards the end of the century because most of the population and buildings within the hazard zones are relocated through the formation of easements. Policies that move people and buildings away from coastal hazards were most successful in protecting property from flooding impacts whereas policies that permit the construction of BPS protect property from erosion impacts.

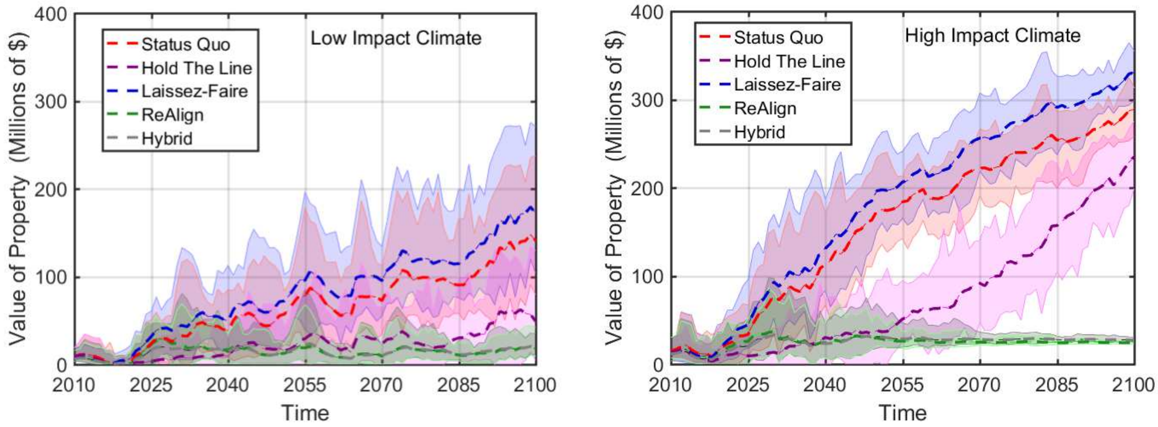

Figure 8: County-wide average assessed value of property impacted by flooding under a low impact climate scenario (left) and high impact climate scenario (right). The dashed line indicates the mean of the climate impact scenario. Shaded bounds indicated the minimum and maximum values.

Comparing costs of policy scenarios over time allows for the evaluation of tradeoffs (Figure 9). BPS construction and maintenance costs in the *Status Quo* and *Hold the Line* policy scenarios were similar early in the century, but diverged towards the end of the century as nourishment offset some of the costs of raising BPS to account for higher TWLs. The greatest expenditures for both BPS construction and maintenance occurred under the *Laissez-Faire* policy scenario, costing ~$250 million between 2010 and 2100 (~$2.5 million per year). The *Hold the Line* and *ReAlign* policy scenarios were most expensive (~$300 million) as a result of nourishment and the creation of easements (under the assumption that the assessed value of the property was equal to the cost of easement creation), respectively.

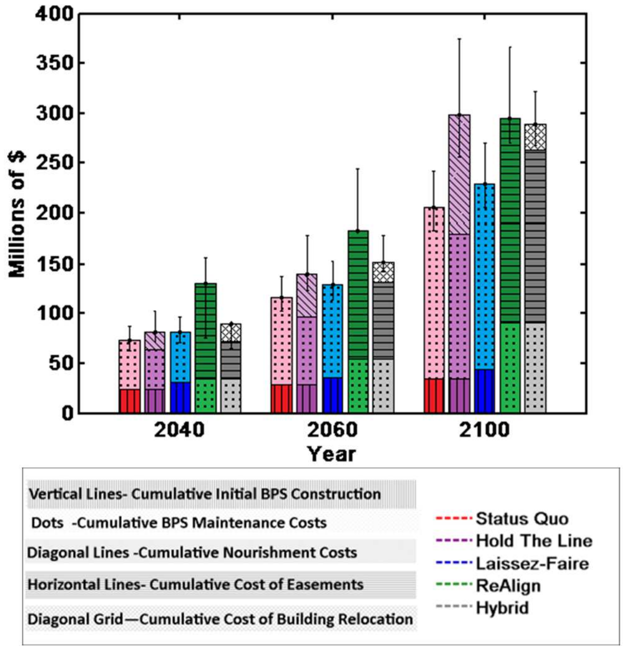

Figure 9. Cumulative costs associated with protecting coastal property across Tillamook County. Bars indicate the mean of the medium impact climate scenarios. Error bars indicate the mean total value under the low and high impact climate scenarios. Costs were based on ESA, 2012.

4.3 Metrics Related to Public Good

Metrics related to public good include (1) the extent of shoreline that was accessible to recreation and (2) the length of road that was impacted by coastal hazards. Within the context of this analysis, beach accessibility was defined as the ability to walk (run, ride, etc.) the beach alongshore (evaluated every 100 meters). Based on stakeholder input, particular sections of beach were considered inaccessible when the maximum daily TWL reached the toe of the dune or structure more than 10% of the year.

By the end of the century, the combination of climate impacts and hardening of the shoreline significantly reduced beach accessibility (Figure 10). Accessibility was greatest under the *ReAlign*, *Hybrid*, and *Hold the Line* policy scenarios, and the most limited access occurred under the *Status Quo* and *Laissez-Faire* scenarios. Beach nourishment in the *Hold the Line* scenario was ineffective under the medium and high impact climate scenarios as the extension of BPS onto the beach in response to higher TWLs prevented the maintenance of accessibility. Under the *ReAlign* and *Hybrid* policy scenarios, the prevention of new BPS construction and relocation of impacted buildings preserved accessibility while under the *Status Quo* and *Laissez-Faire* policy scenarios BPS reduced accessibility by mid-century.

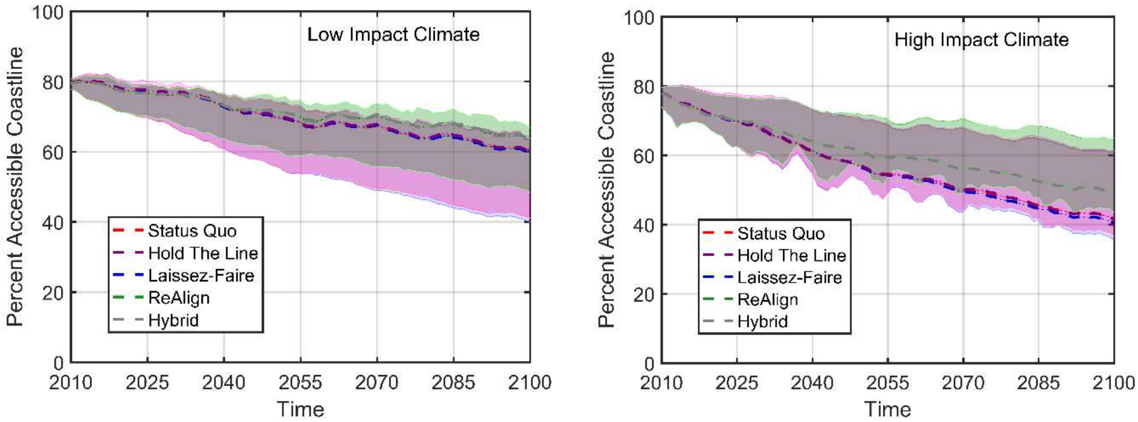

Figure 10. County-wide percent of accessible coastline. Accessibility is defined as the ability to walk, run, ride along the (dry) beach in the alongshore direction. The dashed line indicates the mean of the climate impact scenario. Shaded bounds indicated the minimum and maximum values.

Because the projected population growth rate in Tillamook County is relatively low, current infrastructure was considered sufficient to accommodate the projected growth within this analysis. The length of road impacted by erosion (not shown) was greatest in the *ReAlign* and *Hybrid* policy scenarios (~15km) as a result of lack of new BPS construction. In contrast, the length of road impacted by flooding was greatest in the *Laissez-Faire* policy scenario (~23km) as a result of increased TWLs due to beach narrowing caused by the presence of BPS. Overall, options that relocate people away from the shoreline or preserve current geomorphic conditions through nourishment provide higher accessibility to beaches and roads through time.

A model sensitivity analysis presented in Appendix A suggests that improvement in coastal hazards modeling techniques could potentially refine and improve results. Because landscape metrics were sensitive to values used to parameterize policies, model results are estimates of landscape trajectories rather than projections of future values. However, consistent parameterization between policy scenarios allows for comparative analysis of management strategies under a range of climate change scenarios.

4.4 Assumptions, Limitations and Constraints

Due to the co-developed scope of the Envisioning Tillamook County Coastal Futures Project (Lipiec et al., 2018), a number of limitations and constraints were imposed during the data development and simulation phases of this alternative futures analysis. These include:

1. Only datasets that were available for the entire Tillamook County study area were employed in the analysis.
2. The same policy sets were applied in each community, no sub-regional differences in policies were considered.
3. Population growth was assumed to be the same in all policy scenarios, and was based on only county-wide estimates of population growth for each county provided by the Oregon Office of Economic Analysis.
4. No demographic shifts or corresponding shifts in choice behavior were considered throughout the analysis period.
5. While a probabilistic failure model was considered, there was no accounting for BPS failure (i.e. no erosion could take place once a BPS was constructed).

6. The model capturing yearly maximum inundation extent was binary (the polygon was either flooded or not) and did not account for wave forces upon structures. Polygons within the potential inundation/erosion extent were refined from tax lot size to 100 meter by 10 meter resolution to better capture coastal hazard impacts.
7. Scarcity of resources (e.g. sediment required for beach nourishment) was not accounted for.
8. This project did not include the effects of estuarine flooding on the landscape.
9. This work predominately explored traditional structural solutions to erosion hazards.

Future work being considered for the region will include more detailed coastal flooding approaches, and will explore scenarios focused on optimizing ecosystem services throughout the landscape such as via the planting of various species of beach grasses along the dune for sediment entrapment (Zarnetske et al., 2013).

5. Conclusions

Tillamook County, Oregon, like many coastal communities, will increasingly be faced with the impacts of climate change, including sea level rise, shifts in storminess patterns, and possible changes in the frequency and magnitude of El Niño events. This paper presents a transferable methodology for comparing the effectiveness of coastal hazard adaptation policy decisions under a range of climate impact scenarios using the agent-based modeling framework *Envision*. Combined within *Envision* were three distinct submodels used to represent change processes in the underlying landscape, including a submodel which permits the probabilistic simulation of total water levels to capture flooding and erosion hazards. In addition, five policy scenarios were co-developed with local stakeholders to represent a range of plausible management strategies. Simulated future landscapes resulting from physical and human drivers were compared both on a county-wide scale and within individual communities using a set of metrics related to development, property risk, and public good. The alternative future scenarios explored here were intended as bounds within which researchers, stakeholders, and policy makers can build shared problem understandings, foster agreement around certain desirable and undesirable future outcomes, explore trade-offs, and analyze policy options under different future climates. For example, tradeoffs must be considered when utilizing riprap revetments to reduce the risk of erosion hazards. This analysis indicates that while these structures halt the impacts of erosion to backshore infrastructure, they may simultaneously reduce beach accessibility through the modification of beach morphology and a coincident increase of total water levels and can substantially increase flooding hazards if the crest elevation of the structures is limited so as not to negatively impact the viewshed.

The approach described here can help coastal resource managers consider climate change adaptation and mitigation options by incorporating a greater understanding of the risks of sea level rise and other climate impacts under a range of management options. Methods outlined here to characterize the magnitude, uncertainty, and spatial variability of coastal flooding and erosion, as well as potential changes in property exposure to these hazards, provide insight on changes in hazard exposure over time. While no alternative future presented in this analysis is presumed to forecast the future landscape in Tillamook County, OR, the range of futures allows comparative analysis of a suite of management solutions, and there estimated costs, in order to evaluate their effectiveness with respect to the changing coastal climate and to facilitate a dialog surrounding climate change adaptation planning towards resilience in this hazard-prone region. Furthermore, this approach can assist in the balancing of community development with long-term sustainability and resilience in a manner that is feasible, flexible, and transferable among many growing coastal communities.

6. Acknowledgements

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Appendix A: Model sensitivity to parameters related to human decision making

To determine the usefulness of the model under uncertain policy parameterization, the landscape metrics described above were used to evaluate model sensitivity to various policy triggers. For each parameter used in the model, a minimum and maximum value was simulated in addition to the baseline under a medium impact climate scenario. Baseline (or 'best guess') values were determined predominately based upon conversations with stakeholders or using historic/current values when available. All population parameters were based on the current distribution of people across the Tillamook County landscape. Parameter minima and maxima were intended to capture the possible range of the parameter in order to address the uncertainty within many of the parameters in lieu of a full Monte-Carlo analysis.

The model was considered to be 'sensitive' to a policy or socioeconomic parameter if the value of a metric (i.e. buildings impacted by flooding) differed from the baseline policy scenario value by more than ~10% under a medium impact climate scenario. Of particular interest was how each of the policy parameters impacted exposure to erosion and flooding hazards under the *Status Quo* policy scenario (Figure 13). The only parameter to which the number of buildings impacted by erosion was sensitive to was development preference near the coastline (Figure , left). A larger growth rate near the coast increased the population at risk of erosion hazards. The lack of sensitivity in metrics related to erosion indicates that the triggers for policies related to

BPS were fairly robust. Buildings impacted by flooding indicated higher sensitivity to policy parameters (Figure 13, right). For instance, both the frequency of maintenance and construction height of BPS impacted the exposure to flooding hazards at varying magnitudes throughout the century. Height of BPS construction was most important early in the century, when TWLs were lower on average due to the combined effects of SLR, wave climate, and geomorphology. During this period, the heights of new BPS or elevated BPS were more sensitive to whether the design was specified based on either the average yearly maximum TWL or the greatest of the recent yearly maximum TWLs. Furthermore, the sensitivity of the model to policy parameters was asymmetric. Raising one parameter may have no effect whereas lowering that same parameter may significantly impact a metric. This was true with the policy parameters related to allocation of growth.

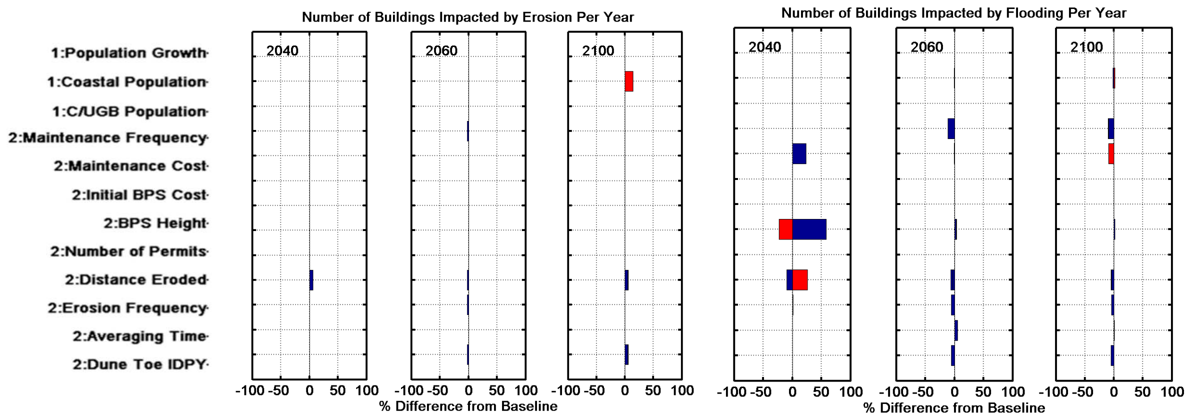

Figure 13: Example of sensitivity analysis for the Status Quo policy scenario for policy parameters included in two policies: (1) Determine urban/community growth boundaries (U/CGB) in accordance with present-day policy and (2) Maintain current BPS and allow more BPS to be built on eligible lots. The number of buildings impacted by flooding (left) and erosion (right) per year, averaged over the decade prior to 2040, 2060, and 2100. Blue indicates the minimum parameter value and red indicates the maximum parameter value. The model was considered sensitive to the policy parameter if the metric was altered by more than 10%.

Time series of buildings impacted by hazards were also used to evaluate sensitivity over time under the *Hybrid* policy scenario (Figure 14). Flooding metrics were only sensitive to the frequency of flooding trigger required to first relocate the building to the safest location within the taxlot or parcel, and following further impacts by flooding in the new location, to relocate that building outside of the coastal hazard zone through an easement (Figure 14, left). Because the metrics shown in Figure 14 were so sensitive to the frequency of hazard exposure, the ability to model the force and depth of inundation events would be an improvement upon the current flooding trigger. Both flooding and erosion metrics were found to be sensitive to the frequency of flooding impacts required prior to relocation of buildings/conversion into easements.

However, this sensitivity was again asymmetric, with greater sensitivity to raising the threshold for relocation and movement of population and buildings outside of the hazard zone.

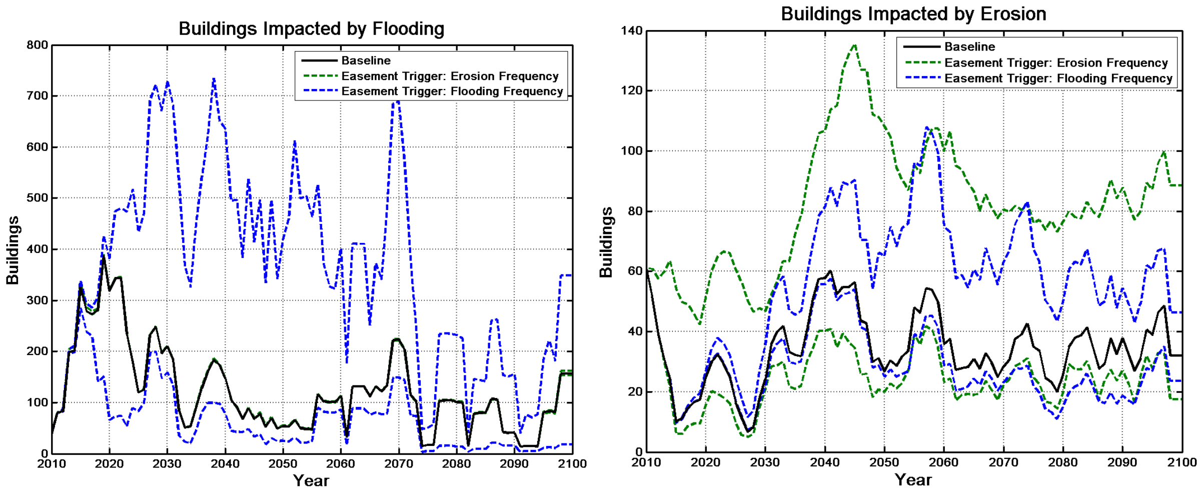

Figure 14: Sensitivity of the number of buildings impacted by flooding (left) and number of buildings impacted by erosion (right) to the frequency of flooding and erosion impacts under the *Hybrid* policy scenario and medium impact climate scenario. The dashed lines surrounding the baseline metric value indicate the range of the metric using the minimum (higher dashed line) and maximum (lower dashed line) estimate. In the figure on the left, the green line is hardly visible as the variability caused by that trigger is minimal.

In total, 16 policies were modeled using 25 different policy parameters, 11 of which were considered significant using the aforementioned threshold. In general, there were four categories of sensitive parameters including those related to BPS characteristics, beach nourishment frequency and cost, criteria for easements, and population allocation. In this application, the model is insensitive to policies focused on restricting new development because the projected county growth rate in the county was relatively slow.

A full discussion of model sensitivity can be found in Mills, 2015,

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