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Evaluating non-indigenous species management in a bayesian networks derived framework, Padilla Bay, WA

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Evaluating Non-Indigenous Species Management In A Bayesian Networks Derived Framework, Padilla Bay, WA

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MASTER'S THESIS

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Evaluating Non-Indigenous Species Management In A Bayesian Networks Derived Framework, Padilla Bay, WA

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Abstract

Many coastal regions are encountering issues with the introduction and spread of non-indigenous species (NIS). There are many vectors that can transport NIS to coastal areas and estuaries. In this study, I conducted a regional risk assessment using a Bayesian networks relative risk model (BN-RRM) to analyze multiple vectors of NIS introduction to Padilla Bay, Washington, a National Estuarine Research Reserve. Bayesian networks models are advantageous because they are parameterized with quantitative data and knowledge, uncertainty can be incorporated into these models, and the calculated risk is described as a distribution of risk for the various endpoints of interest. The objectives of the study were to 1) determine if the BN-RRM could be used to calculate risk from NIS introductions; 2) determine which regions and endpoints were at greatest risk from NIS introductions and impacts; and 3) examine a management option and calculate the reduction of risk to the endpoints if it were to be implemented. Efforts to manage NIS colonization include eradication of the species. This can occur at different stages of NIS invasions, such as the elimination of these species before being introduced to the habitat, or removal of the species after settlement. A management option was easily incorporated into the model to observe the risk to the endpoints if the treatment were to be implemented. This risk could then be compared to the initial risk estimates. The results from this risk assessment indicate the southern portion of Padilla Bay, Regions 3 and 4 had the greatest risk associated with them and the changes in community composition, Dungeness crab, and eelgrass were the endpoints with the most risk due to NIS introductions. The *Currents* node, which controls the exposure of NIS to the bay, was the parameter that had the greatest influence on risk to the endpoints. The ballast water management treatment displayed one percent reduction in risk in this Padilla Bay case study. These models provide an adaptable template for decision makers interested in managing NIS and aquatic environments in other coastal regions and large bodies of water.

Acknowledgements

Doug Bulthuis and Sharon Riggs from the Padilla Bay Reserve provided insight and invaluable knowledge about Padilla Bay, and the native and non-indigenous species that inhabit the bay. Suzanne Shull supplied GIS data from Padilla Bay and Jonah Stinson provided GIS expertise. Eleanor Hines and Kim Kolb Ayre offered guidance on the BN-RRM process. Parts of the research were supported by a contribution from the Bullitt Foundation to the Institute of Environmental Toxicology at Huxley College at Western Washington University.

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INTRODUCTION

Non-indigenous species (NIS) are important stressors impacting coastal waters in conjunction with habitat disturbance (Neubert and Parker 2004, Bossenbroek et al. 2005, Didham et al. 2005, Miller et al. 2010). Many studies have attempted to estimate the impacts of NIS from various vectors of introduction (ballast water, full fouling, and marine debris) (Coutts and Taylor 2004, Lewis et al. 2005, Ruiz and Smith 2005). However, relatively few of these studies analyze the probability of effects from NIS introductions from a landscape scale perspective (see Landis 2003, Colnar and Landis 2007), simultaneously considering multiple vectors of introduction and a broad taxonomic range of NIS. A common theme among NIS studies is a lack of quantitative data (Ruiz and Smith 2005, Davidson et al. 2006, Lee et al. 2010, Sylvester et al. 2011). While some data are available, much of the data is not statistically robust. For instance, detection limits of propagules in ballast water require $30m^3$ to $60m^3$ water samples to be considered reliable for the United States Coast Guard (USCG) Phase I Standards to portray the diversity of organisms and their concentrations in the ballast water (Albert et al. 2010, USEPA SAB 2011). Researchers examining the biofouling of vessel hulls state that the number of vessels analyzed was too small and not necessarily representative of all vessels entering ports (Ruiz and Smith 2005, Davidson et al. 2006).

In my study, I conducted a landscape risk assessment to determine the effects of NIS colonization on coastal habitats and the use of management approaches to reduce propagule concentrations. The model formation and implementation are described using Padilla Bay, Washington, as a case study. However, this approach can be adapted for many bodies of water, such as the Great Lakes, large river systems, coastal areas, and estuaries.

Risk Assessment

In aquatic and terrestrial systems, many natural and anthropogenic factors influence habitats and the organisms that reside in them. Over the past two decades, there has been a movement in the field of ecological risk assessment to understand ecological issues at larger spatial scales (e.g. landscape levels).

In the late 1990s, Landis and Wiegers (1997) and Wiegers et al. (1998) introduced the relative risk model (RRM) that more accurately represents and addresses issues at a landscape scale, analyzing multiple sources of stressors, different habitats and the resulting impacts to the endpoints. The RRM was used to calculate risk to endpoints based on links of stressors entering a habitat (exposure), and an interaction between the stressor and endpoint resulting in an effect. The causal pathways and ranking schemes allowed risk assessors to distinguish the habitats with greatest exposure and endpoints most at risk (Landis and Wiegers 1997, 2005; Wiegers et al. 1998). The RRM was originally created in response to contamination of Port Valdez, Alaska, where multiple sources of pollutants impacted valuable habitats and endpoints (Landis and Wiegers 1997, Wiegers et al. 1998).

In the early to mid- 2000s, the RRM was used to create conceptual models describing pathways of NIS introductions (Landis 2003, Colnar and Landis 2007). Landis (2003) analyzed general vectors of introduction for many taxa of NIS. Colnar and Landis (2007) focused on one species of NIS, the European Green Crab (*Carcinus maenas*), and the Hierarchical Patch Dynamic Paradigm to integrate various spatial aspects. Deines et al. (2005) modeled patch-dynamic interactions and beachhead effects of NIS spread with habitat disturbance from a hypothetical contaminant. Recently, RRM was adapted to use Bayesian networks to estimate risk, such as landscape disturbances to forested habitats (Ayre and Landis 2012), pre-spawn mortality of Coho salmon in the Pacific Northwest (Hines and Landis 2014), mercury contamination in the South River, Virginia (Summers 2012, Johns 2014), and Whirling disease in cutthroat trout (Ayre et al. 2014).

Bayesian networks models, referred to as Bayesian networks or BNs for the remainder of this study, are probabilistic models that create posterior probabilities, in the form of a distribution of risk, based on prior knowledge and data (Hines and Landis 2014). Decision makers and managers can incorporate specific goals and endpoints of interest into the model, then organize information and knowledge in a probabilistic cause-effect fashion. These models can easily examine multiple stressors and evaluate the interaction with habitats and endpoints via linkages representing causal pathways (Pollino et al. 2006). There are many advantages in using BNs, including the ability to process complex systems with high uncertainty, and use the model in a predictive manner (Pollino et al. 2006, Nyberg et al. 2006). Management options can also be included in these models to predict reductions of risk to the endpoints when various treatments are implemented. These factors are important in marine systems where NIS data are sparse and ecological systems complex.

Non-indigenous Species

Over the past five hundred years (Brickman 2006), humans have accelerated the dispersal of NIS through shipping activities, particularly ballast water and hull fouling (Sylvester et al. 2011). Introductions also occurred from the improper disposal of organisms in the packaging of live bait or seafood (Drake et al. 2005, Pimentel et al. 2005, Colnar and Landis 2007). Dispersion of NIS has also resulted from food source relocation (e.g. transplanting shellfish to coastal waters), or from efforts to stabilize and protect shorelines by introducing non-native species (Thompson 1991, Wallentinus and Nyberg 2007).

In my thesis, non-indigenous species (NIS) are defined as species that are introduced to a new coastal system by humans or anthropogenic activities and that impact the community, by causing major alterations (positive or negative) in community structure. The term NIS is used in this paper because there is a negative connotation associated with the term invasive species. The impacts to the community may be losses (e.g. population declines via competition or predation, introduction of diseases, etc.) or benefits, such as providing additional food sources or shelter to native species (Pauley et al. 1986, Fernandez et al. 1993, Cohen et al. 1995). Of the thousands of species introduced to a system, only a few will substantially impact a habitat (Andersen et al. 2004).

Aquatic NIS can influence the environment they colonize by altering habitats and species biodiversity. They can compete with native species for resources (e.g. available habitat, food, or sunlight), prey on native species, and some NIS are known to introduce diseases to native species via food web interactions (Landis 2003, Pimentel et al. 2005, Ruiz and Smith 2005, Colnar and Landis 2007). Some NIS induce physical or chemical changes to habitats (Wallentinus and Nyberg 2007). In Washington State, *Spartina spp*. (cordgrass) was a successful NIS because this plant’s large root system changed the composition of sediments in mudflats (Hacker et al. 2001, Wallentinus and Nyberg 2007). While this species was intentionally introduced, subsequent efforts focused on eradication in the late 1980's and early 2000's after its population expanded beyond control. Millions of dollars are spent every year on damage caused by NIS and on eradication efforts (Bossenbroek et al. 2005, Pimentel et al. 2005).

Additional effects from NIS include reducing biodiversity by altering the evenness of species in ecological communities. Often, NIS become abundant and dominate an area, decreasing the populations of other species (Wallentinus and Nyberg 2007). A diverse community may prevent NIS from establishing and spreading (Andersen et al. 2004). However, settlement and establishment of NIS becomes easier if a system is disturbed (Mack and D'Antonio 1998, Didham et al. 2005). A number of natural and anthropogenic factors, such as pollutants from runoff, overfishing, El Niño or La Niña events (Colnar and Landis 2007), and climate change (Hellmann et al. 2008) can produce habitat disturbances that favor NIS settlement.

Prevention or control of NIS before exposure to the habitat is advantageous to the community dynamics of coastal systems. Bayesian networks derived from the relative risk model (BN-RRM) were constructed to determine risk of NIS introduction and establishment in the Padilla Bay National Estuarine Reserve, Padilla Bay, Washington. Scientific literature and data provided evidence linking the interactions between the vectors, habitats, and resulting impacts to the endpoints. In this risk assessment, the BNs were created using Netica™ software (Norsys Software Corp. Vancouver, B.C. Canada).

Study Objectives

I had three main objectives in this study: 1) determine if the BN-RRM could be used to calculate risk from NIS introductions; 2) determine which regions and endpoints were at greatest risk from NIS introductions and impacts; and 3) examine a management option and calculate the reduction of risk to the endpoints if it were to be implemented. One management option was analyzed, ballast water treatments, to estimate the reduction of NIS entering and influencing the estuarine community. Although the NIS model created in this study was specific to Padilla Bay, it is an adaptable template for other aquatic areas.

My thesis starts with a description of the study site and determination of the risk regions. Next, a detailed account of the Bayesian Networks Relative Risk Model (BN-RRM) process is presented, including the initial construction of the model framework as well as the model parameterization. Two risk scenarios will be discussed, the initial risk estimate to Padilla Bay and risk in a management scenario. The management scenario focuses on ballast water treatments described by the USEPA Science Advisory Board (USEPA SAB 2011). The results from models indicate that the greatest risk occurs to the southern part of the bay and that the *Currents* node (a source of NIS and link of exposure) was the factor that had the greatest influence to the endpoints. Sources of uncertainty are identified in the discussion, as well as the value of using risk assessments in the evaluation of management options.

METHODS

Padilla Bay Study Site

Padilla Bay is an estuarine system in Skagit County, Washington, known for its extensive eelgrass meadows. Tidal fluxes transport water to the bay from the Strait of Georgia (north), Skagit Bay via the Swinomish Channel (south), and Guemes Channel (west); a number of freshwater sloughs also contribute water to the bay. In December of 1980, Padilla Bay was designated as the eighth National Estuarine Research Reserve (PBNERR 2008), and will be referred to as PBNERR.

Padilla Bay is characterized by a flat intertidal zone, much of which drains with ebbing tides (especially during spring tides), and subtidal waters in the channels and along the western edge. Padilla Bay has unique eelgrass beds, covering approximately 3,200 hectares (>7,500 acres) (Bulthuis 1991, PBNERR 2008). The eelgrass beds provide habitat, food, and nursery grounds for many species, such as juvenile salmon, Dungeness crab and other invertebrates, vertebrates (including local and migratory birds), and marine mammals (PBNERR 2008). Habitats in the PBNERR include the intertidal eelgrass beds and mudflats, forests and grasslands, Hat Island, subtidal mudflats, and deep-water habitats (PBNERR 2008).

Land and water use adjacent to the bay is comprised of agricultural, urban, industrial, shipping and recreational activities (e.g. boating and crabbing). Pollutants from these activities can lead to habitat disruption and create available habitat for NIS to settle into. The Padilla Bay watershed drains approximately 23,000 acres of land mainly via three sloughs, Joe Leary Slough, Big Indian Slough, and No-Name Slough, some of which are on the Impaired Water List (PBNERR 2008).

Many non-native organisms currently reside in Padilla Bay. Most of these were introduced with shellfish aquaculture. The Pacific oyster (*Crassostrea gigas*) was intentionally introduced into Samish and Padilla Bay in the 1930s for commercial harvest (Dinnel 2000). The Japanese littleneck clam (*Venerupis philippinarum*) was also introduced for commercial aquaculture (Riggs 2011). Additional non-native species include: eelgrass (*Zostera japonica)*, soft-shell clams (*Mya arenaria*), mud snails (*Nassarius fraterculus and Batillaria attramentaria)*, and the purple varnish clam (*Nuttallia obscurata*) (Dinnel 2000, Riggs 2011). The purple varnish clam was likely introduced from ballast water (PBNERR 2008, Riggs 2011). Parasitic flukes have been found in some snails, especially *Batillaria spp*. (Riggs 2011). Cordgrass (*Spartina spp.*) is still found in the bay; however, eradication efforts have reduced the population to less than 1/10 of an acre (PBNERR 2008).

Determination of Risk Regions

Padilla Bay was separated into four risk regions, based on the watersheds, channels in the bay, and adjacent land use, such as agriculture, industry, forest, and urban areas (Figure 1). The specific boundaries were consistent with earlier work by Bulthuis (1991). The total area of the study site was 61.35 km^2. Geographic Information System (GIS) was used to map the risk regions. Data were obtained from the National Estuarine Research Reserve System Centralized Data Management Office (2013) and Suzanne Shull from the PBNERR.

The habitats within these regions were fairly similar, including mudflats and eelgrass beds, however, adjacent land use varied for each region. Runoff from adjacent lands may disturb aquatic habitats and indirectly facilitate NIS settlement. Region 1 contained urban and farmland areas on the delta plains north and east of Padilla Bay. Possible stressors were non-point source pollution from urban and agriculture land use. Region 2 consisted of forest uplands, urban, and agricultural areas.

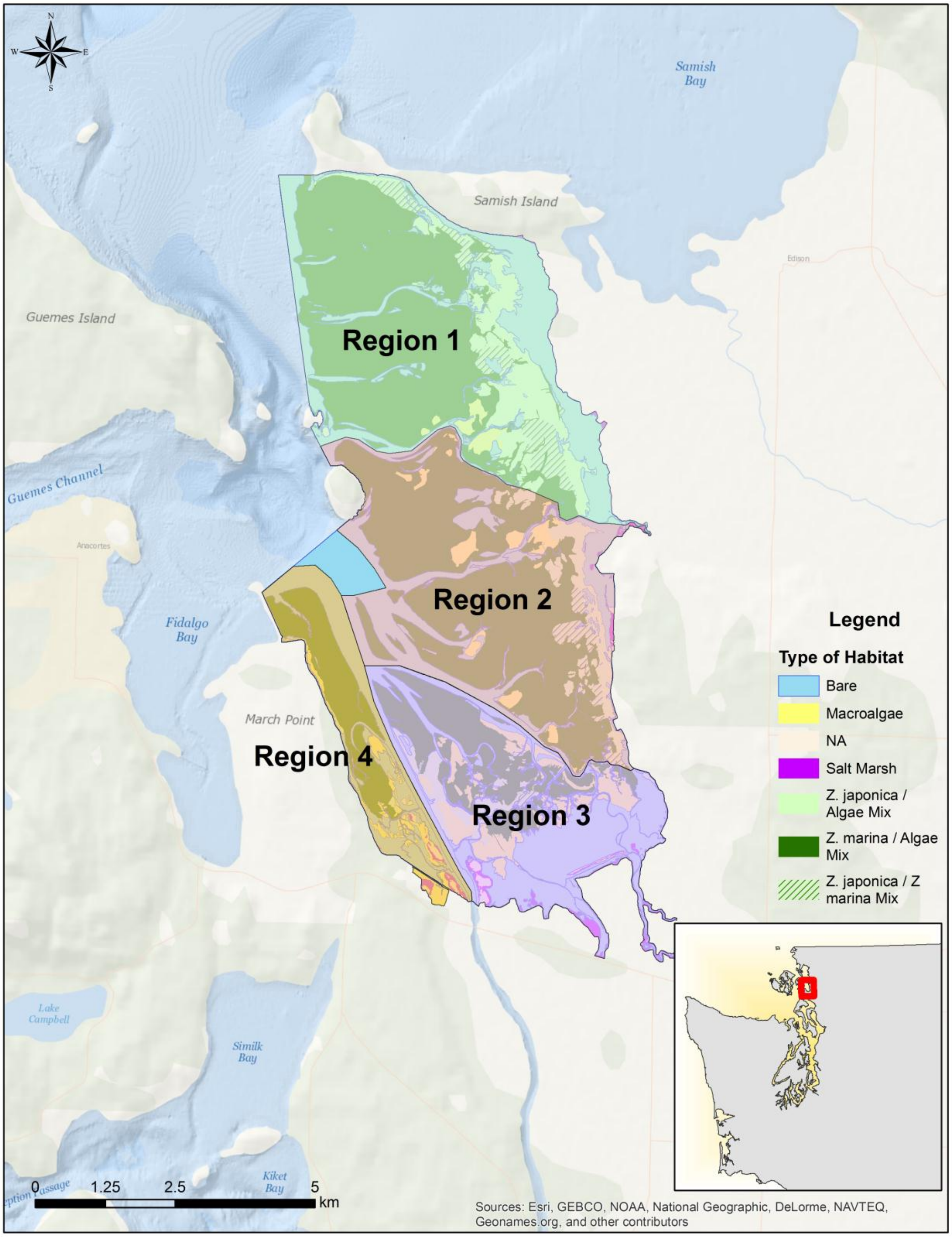

Figure 1. Map of Padilla Bay with the risk regions identified. Risk regions were determined based on watersheds and adjacent land use.

Contaminants that most likely entered the watershed were nonpoint source pollutants from urban and agricultural runoff (e.g. *E. coli* bacteria from pastureland and poor sewage adjacent to Joe Leary Slough (PBNERR 2008)). Region 3 contained stressors from a variety of agricultural and industrial sources, including a seed processing facility and the Burlington Northern Railroad, which transports petroleum products, fertilizer, and feed (PBNERR 2008). The Swinomish Channel, which divides Region 3 and 4, connects Skagit Bay to Padilla Bay and was the route of exposure for the NIS cordgrass, *Spartina spp.* (PBNERR 2008). Region 4, March Point, is heavily industrialized with two large oil refineries and wharf systems that receive oil tankers from various locations around the world (PBNERR 2008).

Exposure of NIS from hull fouling and ballast water discharges was associated with vessels entering March Point and Anacortes ports. Currents transport NIS, depending on the tides, east into Padilla Bay, south into the Swinomish Channel, or west into the Guemes Channel (Bulthuis and Conrad 1995a,b). Additional exposure of NIS arose from hull fouling and ballast water discharge from ports and stationary vessels in the channels north of Padilla Bay and secondary transport of NIS from the south (Swinomish Channel).

Building the Bayesian Network Relative Risk Model (BN-RRM)

Relative risk models are used to conduct risk assessments at large spatial scales with multiple stressors, habitats and endpoints of interest. Landis and Wiegers (2005) provide a detailed description of this process. The construction of the BN-RRM starts with the creation of a conceptual model that is used to map the cause and effect pathways from the sources of stressors to the endpoints. The conceptual model creates the basic framework for the Bayesian networks structure. I used the BNs to expand upon the conceptual model by describing the various states (e.g. low, medium, high) associated with the stressors, exposure, and risk from quantitative data and knowledge. Model parameterization was used to define the states for each node and describe data sources for the input nodes as well as the conditional probability tables (CPTs) for the child nodes. Once model parameterization was complete, the model was run and risk was calculated. To estimate parameter sensitivity, an entropy analysis was conducted to determine the variables that had the greatest influence on the endpoints and also indicate where errors occurred in the model. I analyzed the management scenario and the risk from this option was compared to the initial risk estimate. The distributions of total risk from both scenarios were compared in a Monte Carlo simulation.

Conceptual Model- The conceptual model provided the foundation for the BNs. The NIS conceptual model was based on a model by Landis (2003) as implemented by Colnar and Landis (2007). My model described direct sources of NIS introductions as well as other disturbances influencing the habitats, which provided greater opportunities for NIS to enter and establish. Direct sources of NIS included shipping activities (ballast water discharge and hull fouling), NIS attached to marine debris, climate change (movement of NIS north with warming waters), and currents dispersing the NIS thus providing exposure of NIS to the bay. Indirect factors included chemical pollutants and disturbances from urban, agricultural, and industrial sources that affected water quality and community interactions (Figure 2). While this specific assessment analyzed the impacts of NIS to Padilla Bay, discovering links between the direct and indirect sources provides additional information on patches where NIS could successfully invade.

Before delineating the conceptual model, the endpoints of interest were determined. Discussions with stakeholders from the PBNERR revealed the species and endpoints of greatest interest. These included juvenile salmon (pink and chum), harbor seal, Dungeness crab, eelgrass (*Zostera marina*), and a variety of birds, some permanent residents, such as the Great Blue Heron, and other migratory birds that only winter in Padilla Bay, such as the Black Brant. Diving and dabbling ducks were also birds of interest for recreational purposes such as hunting and birding. Additional endpoints considered were water quality and changes in community composition. Once the endpoints were identified, the potential sources of stressors affecting the endpoints were determined. Literature searches were conducted to establish causal linkages from the stressors to the habitats (exposure), and the resulting effects to the endpoints. The exposure and effect linkages were essential in determining if the stressor arrived at the habitat and if the endpoint used that habitat. If the stressor was not exposed to the habitat or the endpoint did not utilize the habitat, then there was no expected effect to the endpoint. All of this information was incorporated into a conceptual model of Padilla Bay

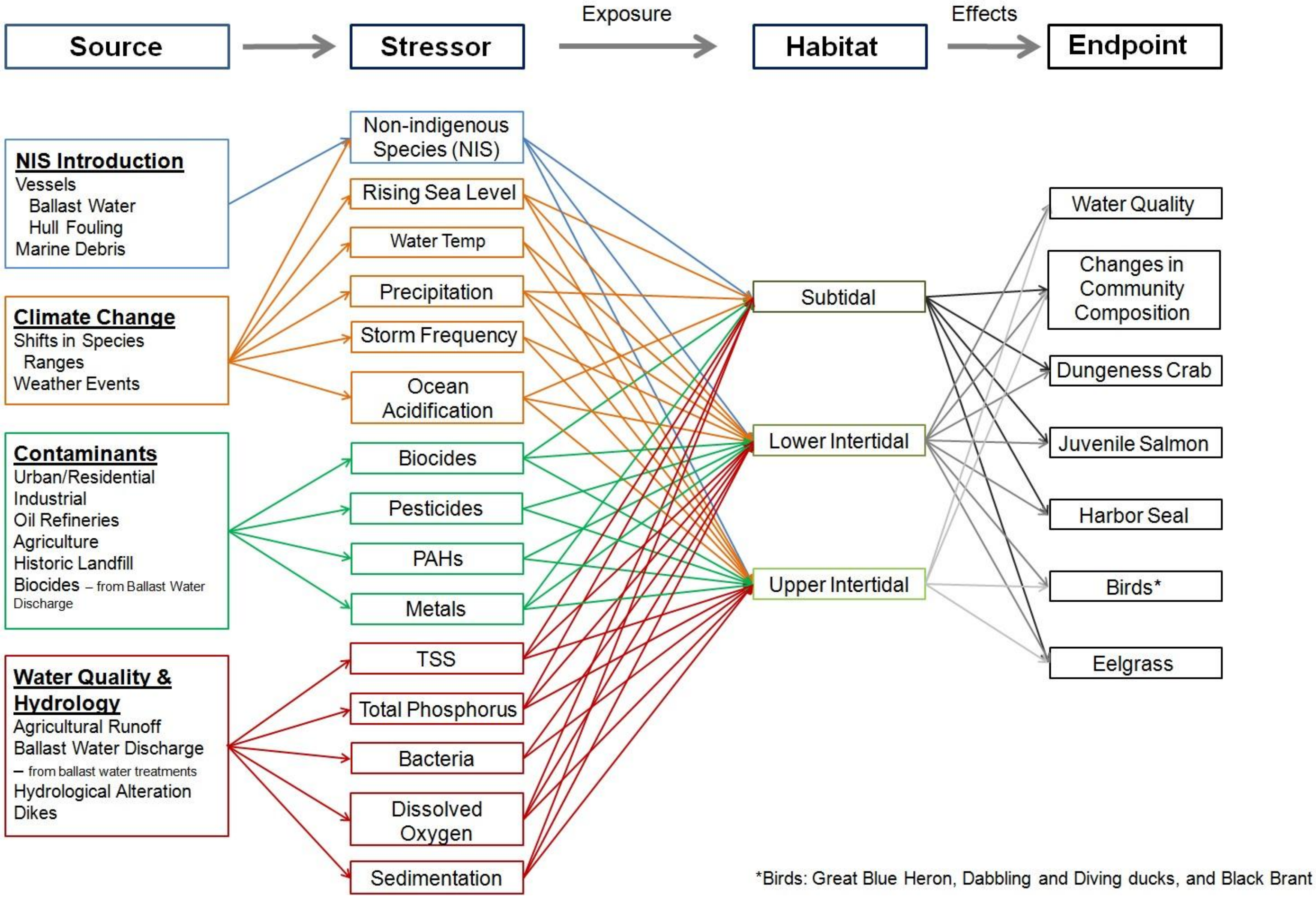

Figure 2. Conceptual model displaying all of the sources of stressors, habitats and endpoints for the Padilla Bay risk assessment. This is an overview conceptual model; each of the different sources of stressors has a separate conceptual model (below).

(Figure 2). This conceptual model was then separated into four smaller conceptual models: climate change, water quality and hydrology, contaminants, and NIS models (Figures 3-6). This study focused on the NIS model; the other three conceptual models will be completed at a future time.

The NIS conceptual model is illustrated in Figure 3. The causal pathway consisted of the vectors of introduction (ballast water, hull fouling, marine debris, and secondary transport of NIS) dispersing organisms, both early life stages and juveniles (ELSJ) or adult organisms. Currents transported the organisms to various habitats in each region. Once in the habitat, the NIS had to settle, establish, spread, and have an effect on the habitat or endpoints.

Andersen et al. (2004) identified four steps necessary for a species to become a NIS. First, a species must physically arrive at a new location. Second, a species has to establish itself by reproducing and expanding its population. If this does not happen, local extinction occurs. Third, the population must spread from its point of entry, finding available space in the surrounding habitat. Lastly, the species has to impact the community via competition for resources or alteration of the habitat. Naturally occurring filters, such as lack of settling cues and predation before settlement, make it difficult for organisms to complete all stages of colonization and affect coastal communities. Many species progress to the third stage and coexist in a habitat with other organisms (Andersen et al. 2004). Allee effects, patch dynamics, and population models help determine these interactions (Deines et al. 2005, Colnar and Landis 2007, Lee et al. 2010). Various life history stages of the organisms should also be considered. Determining if one stage more readily establishes over another is important information that should be incorporated into this risk assessment when data are available. All of the factors discussed above were considered in the construction and parameterization of the conditional probability tables in the BNs.

Bayesian Network Structure- The conceptual model provided the framework for the Bayesian networks (Figure 7). In the BNs, I utilized quantitative data and knowledge to calculate the risk of NIS impacting the endpoints of interest. Each box in the conceptual model represented a node in the BN. Names and discussions of specific nodes throughout my thesis are distinguished by italic font. All nodes in the model were classified as nature nodes, which represented either probabilities of the

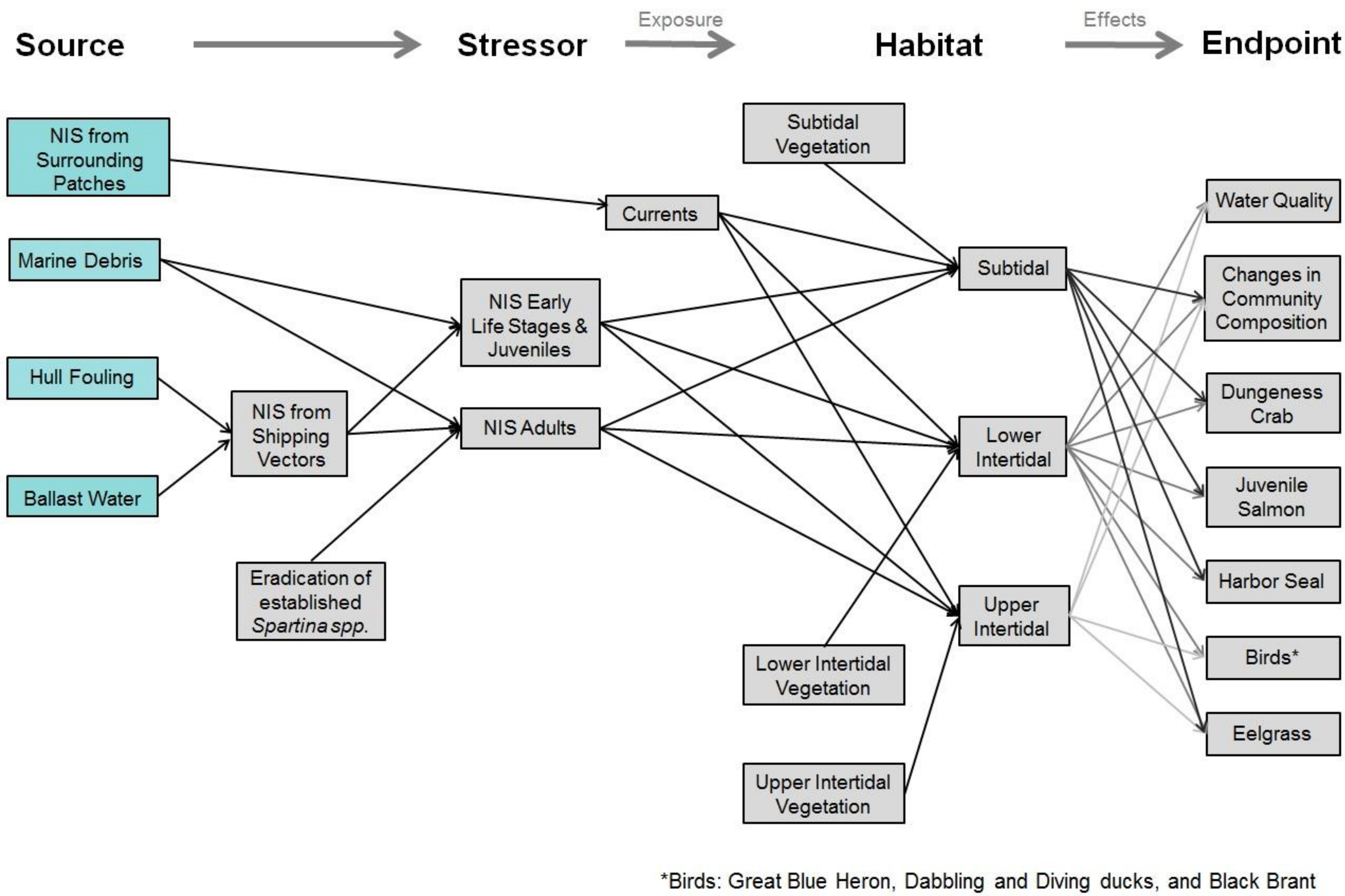

Figure 3. Conceptual model for the NIS vectors of introduction. This model displays the vectors of introduction (teal boxes). The *NIS from Surrounding Patches* are patches external to Padilla Bay. This model provides the structural framework of the Bayesian model.

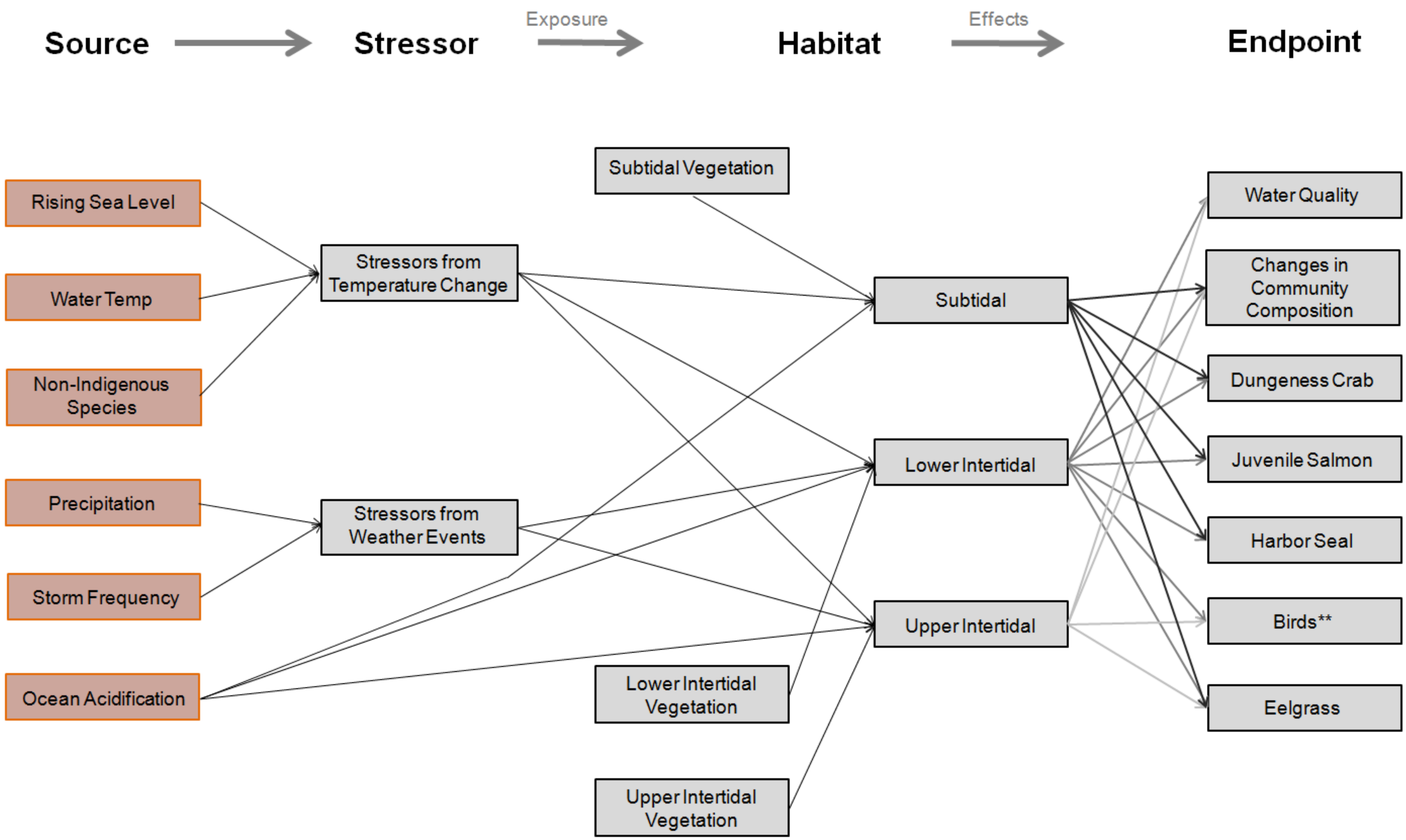

Figure 4. Conceptual model for the Climate Change sources of stressors.

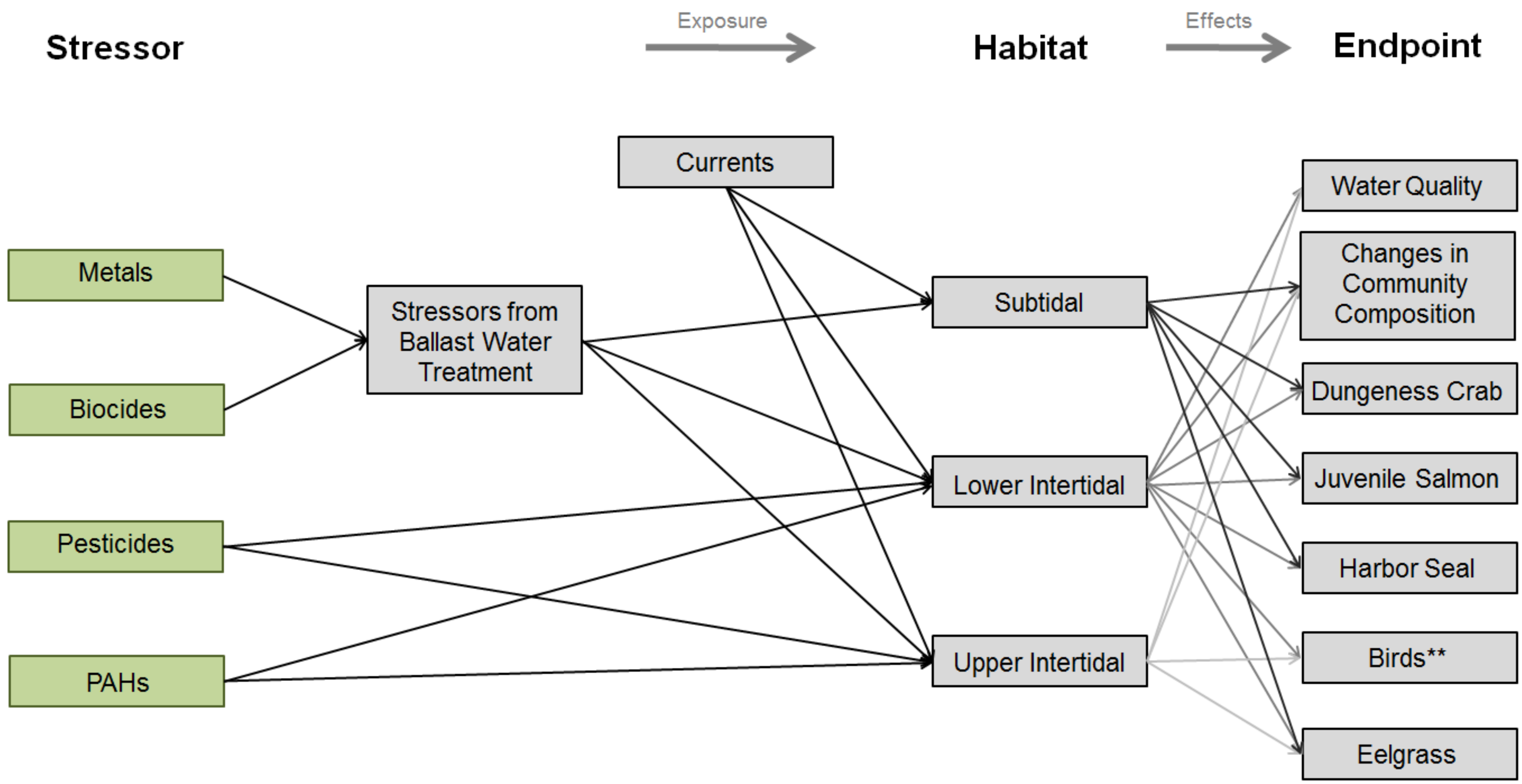

Figure 5. Conceptual model of Contaminants entering Padilla Bay. Note that the Biocides stressor originates from the chemical treatments of ballast water management systems. Many of these chemicals will be of chlorine origins or chlorine by-products.

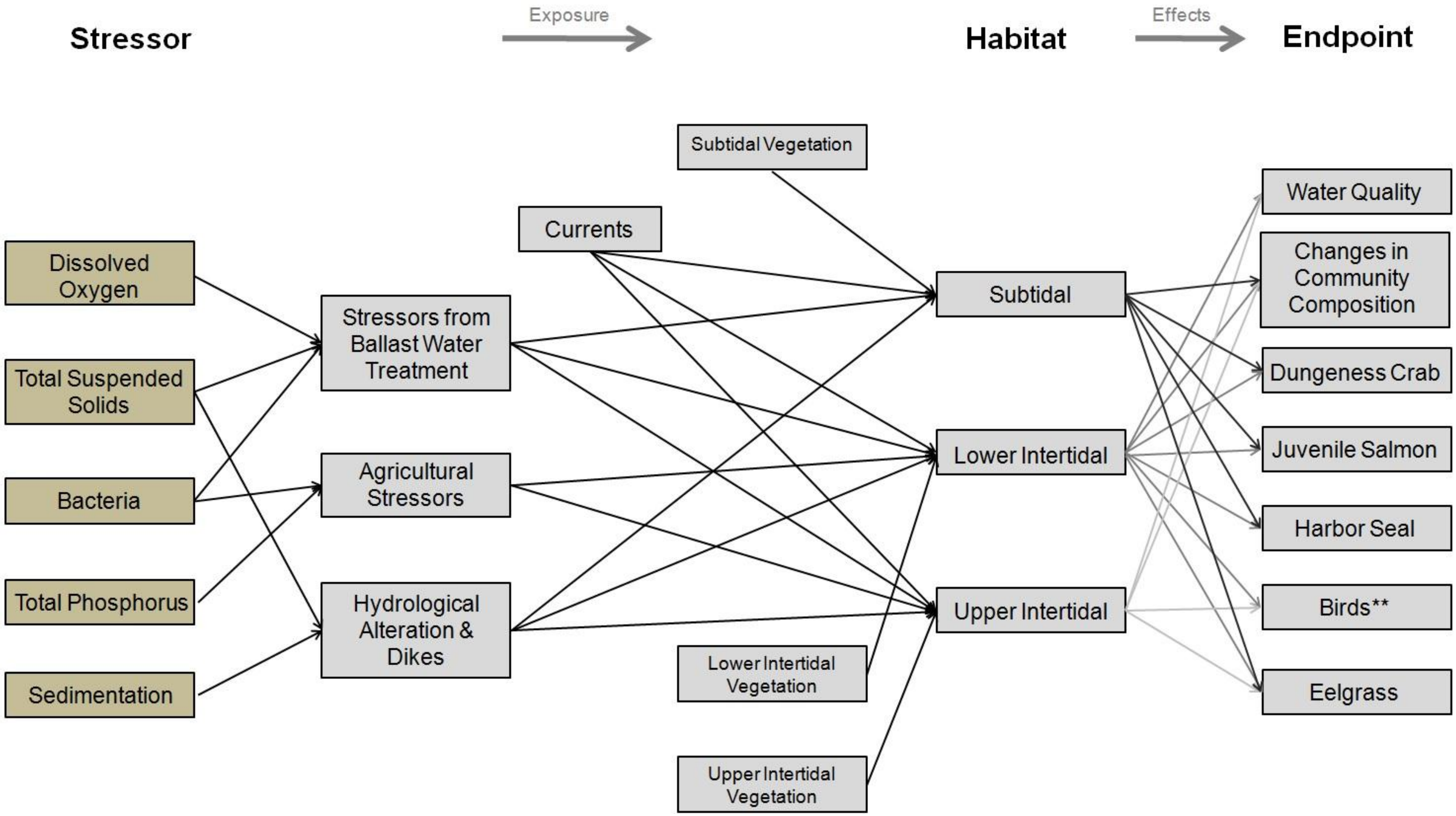

Figure 6. Conceptual model for Water Quality and Hydrology of Padilla Bay. Note that the Dissolved Oxygen (DO) and Turbidity may have terrestrial causal pathways or may be stressors originating from ballast water treatment systems. Low DO may result from deoxygenation treatments and increased turbidity may be a consequence of cleaning (backwashing) the filters used in the mechanical/physical treatment systems. Bacteria can originate from terrestrial sources (waste products from livestock) or from ballast water effluent.

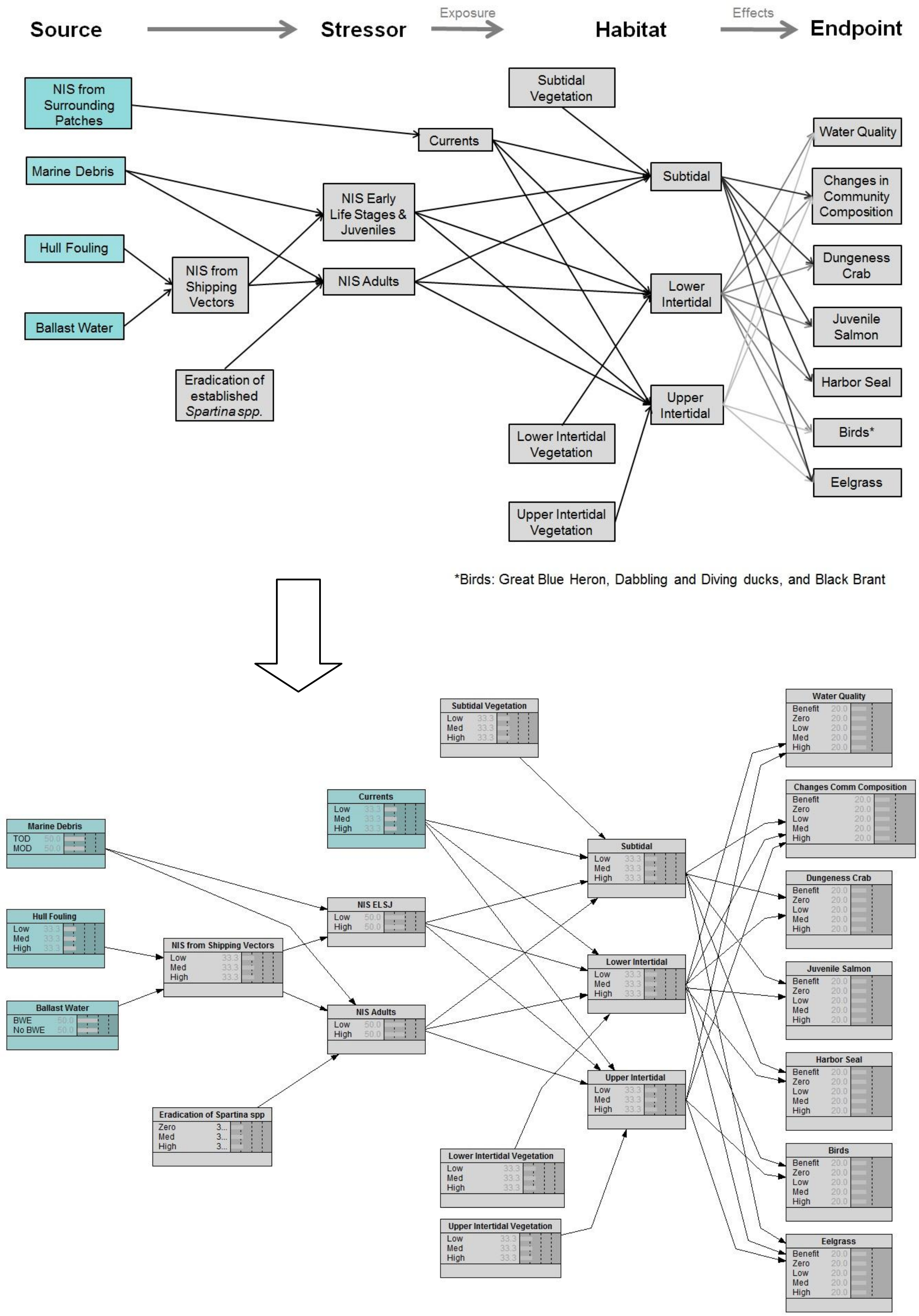

Figure 7. Conceptual Model transformation into the Bayesian Model (BNs). The conceptual model (top) provided the structural framework for the BNs (bottom). The BNs quantitatively define the risk to each of the endpoint nodes in the model. The distribution bars in this figure are gray and all states in each node are set to an equal distribution because the model has not been parameterized and no risk calculations have occurred.

various states, or a fixed state. Uncertainty was incorporated into the nodes with limited data or knowledge. All of the nodes (except fixed nodes) were assigned some uncertainty, which accounted for the tails in a distribution curve. Fixed nodes had no uncertainty associated with them because only one state was possible for that variable. If no data were available to distinguish between the various states, the node received a uniform distribution. Nodes generally had three states, with the high state usually corresponding to greatest probability of the stressor or exposure occurring. Exceptions to this were the management nodes in which the high state represented the greatest reduction of the stressor. Binomial states were used for the *Ballast Water*, *Marine Debris*, and *Life Stage* nodes, when only two options for the node existed. For the vectors of introduction, *Marine Debris* and *Ballast Water*, binomial nodes were used due to the type of data available, whereas the *NIS Life Stages (ELSJ or Adults)*, the two states (low and high) were used because there was not enough data to distinguish between three states (due to the uncertainty associated with these parameters). The endpoints in this model contained of five states, the additional states representing benefits provided by the NIS and a zero risk state. I determined the number of states for each node based on the availability and quality of data and scientific literature for each variable.

The BN structure contained various tiers (Ayre and Landis 2012). The first tier represented the parent or input nodes, which were distinguished as the nodes with no links (arrows) entering them. The second tier consisted of child nodes. They were the nodes with the links feeding into them indicating a probabilistic relationship with the parent nodes. The last tier included the endpoint or impact nodes, which presented the expected risk from the stressor, habitat, and endpoint interaction. If two nodes interacted with one another, they were linked with an arrow. After the structure of the model was completed, I parameterized each node by defining the states and ranks for all of the nodes (Supplementary Table 1) and the conditional probability tables (CPTs) for the child and endpoint nodes.

Model Parameterization: Initial Risk Estimate- The BN was parameterized with a combination of quantitative data, federal regulations, and knowledge from peer-reviewed scientific literature and technical reports (see references from Supplementary Table 1 - Model Parameterization). Model parameterization had two steps. First, the states for each node were defined, for example, a low state for *Hull Fouling* was defined as ships that had been dry-docked within the last 14 months (Supplementary Table 1). Second, the CPTs were completed with available data or prior knowledge about the parameters and interactions between them. The CPTs quantitatively analyzed the probabilistic distributions for every combination of the parent nodes entering the child node. Evidence from peer-reviewed scientific literature and technical reports were used to determine the probabilistic exposure-response interactions for each combination of parent nodes in the CPTs. Citations of this literature can be found in the Model Parameterization table (Supplementary Table 1). The model parameterization process for each node is described below.

Vectors of Introduction- The vectors of introduction analyzed in this BN-RRM were ballast water, hull fouling, marine debris, and the secondary transport of NIS from currents (see *Currents* below). Data sources for the vectors of introduction included: the National Ballast Information Clearinghouse (NBIC 2008) for the ballast water discharge data and Ocean Conservancy International Beach Clean-up data for the state of Washington for the marine debris data. No data were available for the hull fouling vector of introduction, thus an equal distribution was given to each state (33.3% for low, medium and high states).

The NBIC data consisted of ballast water discharge forms submitted by vessels to the receiving ports. These forms indicated the last port of call, volume of ballast water on board, and the location, type, and volume of ballast water exchanged (flow through or empty-refill exchange). The forms also stated if an alternative ballast water treatment was used in any of the ballast tanks. In analyzing the records for this assessment, I noted whether or not a ballast water exchange was performed (BWE or No BWE) or if a ballast treatment was implemented for each ship entering the Ports of Anacortes and March Point from January 2011 through December 2013. I calculated the frequencies of how many vessels had undergone a BWE versus how many vessels had not undergone a BWE. I then summed the vessel arrivals for the three years and divided each number (the summed BWE and summed No BWE) by the total vessel arrivals to determine the probability of each of these states occurring. Forms missing data and vessels that did not discharge ballast were not used in the assessment. Ships with incomplete ballast water exchanges were counted as 'No Ballast Water Exchange'. Discharge of ballast water without an exchange resulted in a higher discharge of propagules into the receiving ports (Minton et al. 2005). Discharge after a mid-ocean ballast water exchange reduced the concentration of coastal propagules and likely the number of possible NIS (Minton et al. 2005). Most vessels that did not exchange their ballast water were coastal voyages and were traveling within the common water agreement, WA Rev Code § 77.120.030. However, these vessels could aid in the secondary transport of NIS (Lawrence and Cordell 2010).

Marine debris data were collected by the organization Ocean Conservancy during their annual International Beach Clean-up. Only debris data collected in the state of Washington were used. Debris were classified as marine origin debris (MOD) such as buoys, floats, and other items submerged in the water before becoming debris, or terrestrial origin debris (TOD), which consisted of debris initially originating on land before being washed into the ocean. The data collected only analyzed the type of debris; no analysis was conducted on the taxonomy of organisms attached to the debris.

NIS from Shipping Vectors- The *NIS from Shipping Vectors* node combined probabilities of stressors from ballast water discharges and the fouling of ships hulls. These vectors were given similar probabilities associated with the introduction of NIS, as both of these vectors were equally likely to introduce NIS to coastal regions (Ruiz and Smith 2005, Davidson et al. 2006). This was reflected in the probability distributions in the CPT. For instance, the parent combination of medium hull fouling and No Ballast Water Exchange (No BWE) was given the same probabilities as the high state of hull fouling and a BWE for the ballast water node (Table 1). In the ballast water node, the BWE was equivalent to medium effect or probability of NIS introductions.

Life Stages of NIS- The life stages of NIS were separated into early life stages and juveniles (ELSJ), and adult NIS. The ELSJ were associated with all vectors of introduction, whereas the adults were primarily associated with the hull fouling and marine debris vectors, and to a smaller extent, the ballast water. The intake pipes (sea chests) in ballast water systems have grates covering them (15-25mm), restricting the size of larger organisms taken in the ballast water and discharged into the

Table 1. Conditional Probability Table (CPT) for the *NIS from Shipping Vectors* node. The ballast water exchange (BWE) in this risk assessment was equivalent to medium effect.

Parent Nodes		**Child Node States**		
Hull Fouling	**Ballast Water**	**Low**	**Medium**	**High**
Low	BWE	30	30	40
Low	No BWE	10	40	50
Med	BWE	10	30	60
Med	No BWE	0	20	80
High	BWE	0	20	80
High	No BWE	0	5	95

receiving ports, though it is possible for adults to be discharged in ballast water (Coutts 2003). Adult organisms found on the hulls of ships and on marine debris had the chance of becoming dislodged and entering the bay and surrounding waters; however, they could have also reproduced and released propagules into the water (Coutts & Taylor 2004, Ruiz & Smith 2005, Sylvester et al. 2011). I gave the parent combinations (*NIS from Shipping Vectors* and *Marine Debris*) a greater percent or probability to the low state in the CPT of the *NIS Adult* node and a greater probability to high state in the *NIS ELSJ* node. The probabilities varied by 5-30% depending on the various parent combinations. Essentially, this represented less probability of introductions of NIS from adult stages than the ELSJ stages.

Eradication of Spartina spp.- This is a management option that reduced NIS populations already established in Padilla Bay. This approach is a species-by-species removal and usually consists of combinations of chemical and mechanical eradication in an attempt to eliminate NIS. The cordgrass, *Spartina spp.*, covered approximately 17 acres of tidal flats in the southern part of Padilla Bay in the late 1990s. Eradication efforts reduced this population to less than 1 acre (PBNERR 2008). Medium eradication was applied to the *Eradication of NIS* node in Region 3 for both scenarios (initial risk estimates and the management scenario). The ranking scheme for the low, medium and high states in the ballast water management treatments (zero: 0-89.9% reduction, medium: 90-99.98% reduction, and high: 99.99-100% reduction) was also used for the *Eradication of Spartina spp.* node. Complete eradication is very difficult to accomplish, in fact, propagules of *Spartina spp*. are transported yearly from Skagit Bay via the Swinomish Channel (Riggs 2011). Further, removal of one NIS may provide available habitat for another NIS population to enter and settle.

Currents- Currents were the source of exposure of NIS to the habitats and a vector of introduction. Currents transport NIS from the ports (March Point and Anacortes) to Padilla Bay. However, currents can also transport NIS from surrounding established (external) patches to Padilla Bay. For instance, *Spartina spp.* propagules from Skagit Bay are transported via currents to Padilla Bay through the Swinomish Channel. Three main sources of water filled the bay: water from Guemes Channel (includes Anacortes and March Point ports), water from Skagit Bay via the Swinomish Channel, and currents from the Strait of Georgia (north). While the Ports of Anacortes and March Point were the closest to Padilla Bay, the currents from the north and south were also possible sources of transport of NIS to the bay. This includes hull fouling NIS from vessels and tankers waiting in waters north of Padilla Bay to enter the March Point refinery docks and other established patches in Skagit or Samish Bays. Drift stick studies conducted by Bulthuis and Conrad (1995a,b) were used to understand water movement from the south (Swinomish Channel) and west (Guemes Channel). Exposure pathways via currents from the north are not well understood so uncertainty was assigned in the input distributions for the *Currents* node. This is apparent especially in Regions 1 and 2 with fairly equal distributions.

Subtidal, Lower Intertidal, and Upper Intertidal Vegetation- GIS data, ESRI shape files of vegetative habitat of Padilla Bay from the SWMP Biomonitoring Pilot Site, 2004 (Bulthuis and Shull 2006), and the software program ArcMap were used to determine the percent cover of vegetation for the subtidal, lower intertidal and upper intertidal habitats. I divided the area of vegetation by the total area for that habitat to determine the percent cover of vegetation (e.g. the area of subtidal vegetation was divided by total area of subtidal habitat). The percent cover (area of lower intertidal vegetation divided by the total area of the intertidal habitat) was slightly different for the lower and upper intertidal zones. The same calculation was used for the upper intertidal habitat.

In Padilla Bay, the subtidal vegetation consisted only of *Z. marina*. The lower intertidal vegetation was comprised of *Z. marina* and macroalgae. *Zostera japonica* was the distinguishing factor between the lower and upper intertidal zones, since it is only found higher in the intertidal zone (Phillips 1984).

Although *Z. japonica* preferred the shallower waters, there was still an overlap zone where *Z. japonica* and *Z. marina* coexisted; this region was considered the upper intertidal zone. Other upper intertidal vegetation included *Z. marina*, macroaglae, and salt marshes.

The total vegetated area in each region affects the probability of settlement and establishment of NIS. If a region had more vegetation, it most likely had a developed community structure and greater diversity of organisms (Phillips 1984). This created more difficult conditions for NIS to enter, settle, and establish (Didham et al. 2005, Andersen et al. 2004). If a habitat had less vegetation, more habitat remained available for NIS to enter, settle, establish, spread and invade surrounding areas (Didham et al. 2005).

Habitats- Habitats were classified as subtidal, lower intertidal, and upper intertidal zones, as determined by GIS data. The probability of exposure associated with each region was determined based on the interaction of two factors: propagule supply and the settlement of NIS. Propagule supply included the probability of NIS from various life stages and the exposure of NIS to the habitats via currents. The settlement of the NIS represented the likelihood of successful settlement considering the interactions of available habitat and biodiversity of the community. The subtidal habitat was assigned a greater probability in the medium and high states in the CPTs of the habitat nodes. This indicated a higher likelihood of NIS introductions due to the greater exposure of NIS than the other habitats (currents entering from any direction must first pass over the subtidal habitat). The upper intertidal zone had the least exposure, but more available habitat and a lower biodiversity. Conversely, the lower intertidal habitat had a greater probability of exposure, but a smaller probability of settlement due to less available habitat and a greater biodiversity of organisms. These interactions were reflected in the various combinations of parent states in the CPTs.

Endpoints- Seven endpoints were considered in this BN-RRM: water quality, changes in community composition, Dungeness crab, juvenile salmon, harbor seal, birds, and eelgrass. These endpoints are of interest to the stakeholders because they represent commercial fisheries (e.g. salmon and Dungeness crab). These species also represent recreational activities such as birding, duck hunting, crabbing, and marine mammal watching. The extensive eelgrass meadows provide protected habitat and food sources for juvenile species (salmon, Dungeness crabs, as well as other fish and invertebrate species) and wintering birds. A ranking scheme was implemented to incorporate multiple impacts or effects from various NIS to the endpoints. I developed the ranking scheme based on evidence and data from peer-reviewed literature. Citations can be found in the Model Parameterization table (Supplementary Table 1). Three ranking scheme categories were created for the endpoints: the length of time spent in the habitat, losses, and benefits. The losses for the species endpoints included interactions such as competition and predation between native and NIS species, as well as the susceptibility of native species to diseases or biotoxins (e.g. harmful algal species) from the NIS. Additional habitat and food sources associated with the introduction of NIS were the benefits to the native species (endpoints). The combined rank from these three categories and the relationships between habitats nodes were then used to determine the probability associated with each state (e.g. Benefits, Zero, Low, Medium, and High) (Supplementary Table 2).

The ranking scheme varied for the *Water Quality* and *Changes in Community Composition* endpoint nodes (Supplementary Table 2). The losses for the water quality endpoint were diseases, biotoxins, bacteria, decreased dissolved oxygen concentrations and increased turbidity levels. Water filtration was a benefit associated with NIS. Diseases, changes in sediment composition and chemistry, and changes in the physical structure of the habitat were the losses linked to changes in community composition and a benefit was the creation of habitat for native species.

Management Scenario

A management scenario was incorporated and analyzed in this BN-RRM. In the figure for each model, the red-brown nodes represent the management scenario options. The management scenario analyzed in this case study was reduction of propagules via ballast water treatments. Two options were analyzed for reduction of propagules in ballast water: physical separation (filtration) and physical/chemical treatments (e.g. electrochlorination, chlorine dioxide, deoxygenation and cavitation, UV, and UV + titanium dioxide). Often, these treatments are paired (e.g. filtration + UV) to maximize propagule reduction (Albert et al. 2010, Lloyd's Register 2010, USEPA SAB 2011). The management scenario represented the highest possible level of stressor reduction from the mitigation treatments and provided data on the expected reduction of risk to the endpoints. The ballast water treatments were set to high reduction, with the exception of *Physical Separation*, in which a medium reduction state was used because a high reduction was not possible due to limitations in filter sizes.

Model Parameterization: Management Scenario – The ranking of the management nodes (red-brown) were based on the ability of the treatments to reduce the concentrations of organisms in the ballast water. A ranking of high indicated a greater reduction of propagule pressure than a ranking of zero. The zero state represents reductions of 0-89.9%. While the upper bound may seem high, ballast water exchanges (BWE) can reduce propagules by 90% (Minton et al. 2005), therefore, successful ballast water treatments need to have reductions ≥90%. To obtain a moderate ranking, vessels needs to have an efficacy of 90-99.98%, and high rankings needs 99.99-100% reduction rates (Supplementary Table 3). These reduction rankings were calculated based on the USCG Phase I Standards, which are regulations on allowable organism concentrations in discharged ballast water. The Phase I Standards are described in Supplementary Table 1 and in Albert et al. (2010), Lee et al. (2010), and USEPA SAB (2011).

Physical Separation- The physical separation or filtration treatment removes larger organisms such as zooplankton, but not the smaller organisms (e.g. bacteria and viruses). The filter sizes range from 10-100μm (Albert et al. 2010, Lloyd's Register 2010), so any organism < 10μm could enter ballast water tanks. Because of the limit from the physical treatment, it alone is unlikely to pass the USCG Phase I Standards and so a medium reduction was assigned. Filtration is often used in conjunction with other treatments to remove the larger organisms before the physical and/or chemical processes are applied. Backwashing of the filters may increase turbidity in ports, a possible consequence of this treatment.

Physical/Chemical Treatments- These treatments included two categories, biocidal and physical-chemical processes. Currently, the available literature does not distinguish if one treatment is more efficient at removing organisms than the other, so these categories were generalized as physical/chemical treatments. Biocidal treatments consisted of treating the ballast water with either chlorine dioxide or electrochlorination techniques. Chlorine may not be effective at eliminating cysts

(Lloyd's Register 2010). It is beneficial to use an initial filtration step with chemical processes to reduce the amount of chemical needed to eliminate organisms.

Physical-chemical processes included deoxygenation + cavitation, UV, and UV + titanium dioxide (TiO_2) treatments. The effectiveness of the physical-chemical processes depends on the voyage length and an initial filtration step. Deoxygenation treatments require a minimum transport time of 1-4 days to deplete oxygen in ballast water and eliminate organisms (Albert et al. 2010). Some organisms can survive this period of low oxygen concentrations (Lloyd's Register 2010). Deoxygenation can be paired with cavitation, which interferes with cell wall and membrane functions (Lloyds Register 2010). The UV radiation denatures the DNA of organisms and can eliminate cysts and viruses (Lloyds Register 2010). In turbid waters, UV will not be as effective in eliminating organisms due to limitations in the depth the UV radiation can penetrate the water column (Lloyd's Register 2010). Consequences of this treatment option include possible introduction of decreased DO levels and/or increased turbidity to the receiving ports.

Ballast Water Treatments- The CPT of this child node was based on the ability of vessels to pass the USCG Phase I Standards. Passing these standards depended on the percentage of propagule reduction and the initial concentration of organisms in the ballast tanks (Table 2). To pass the Phase I Standards, fewer than 10 organisms/m^3 were allowed for the zooplankton category (≥50μm). Though many vessels discharged ballast water with concentrations of <3,000 organisms/m^3, some ships have discharge concentrations of >50,000 organisms/m^3 (Minton et al. 2005). In a distribution, ships with such high concentrations of propagules would fit in the tail of the curve. To pass the Phase I Standards with an initial concentration of >50,000 organisms/m^3, a reduction of 99.99% was required. At the upper bound of the zero state (89.9%), vessels with <100 organisms/m^3 could pass the standards. The CPT calculations are described in Supplementary Table 3.

NIS from Shipping Vectors- This node changed in the management scenario due to reductions of organisms from ballast water treatments. The zero state in the management nodes equated to the greatest exposure of organisms and possible NIS introductions, the medium state referred to

Table 2. Percent reduction of propagules required to pass the Phase I Standards for various initial concentrations of propagules per meter cubed of water. I calculated these values to show that is possible for vessels to pass the Phase I Standards with medium propagule reduction rates (90-99.98%). However, note that above 2,000* organisms/m^3 in the ballast water, 100% reduction is needed to pass the Phase I Standards of <10 organisms/m^3 water.

Initial Concentration of Propagules (per m^3)	Percent Reduction of Propagules	Final Concentration of Propagules (per m^3)
100	90%	10
200	95%	10
300	97%	9
400	98%	8
500	98%	10
1,000	99%	10
2,000*	99.5%	10
3,000	99.7%	9
10,000	99.9%	10
25,000	99.97%	8
50,000	99.98%	10

moderate reduction and the high state indicated high reduction of propagules. In the CPT, combinations with high management indicated lowest exposure of organisms to the receiving waters.

Risk Calculations and Entropy Reduction Analysis

Upon completion of the model parameterization for both the initial risk estimates scenario and the management scenario, I compiled and ran the models for each region. After running the models, I completed a sensitivity analysis for each endpoint.

Sensitivity and Uncertainty Analysis: Entropy Reduction Analysis- When working at a regional spatial scale, uncertainty will always be present. This was especially true when interactions between species are unclear and data are missing for various regions or stressors. I encountered both of these situations in this BN-RRM for marine NIS data. Sensitivity tests, entropy reduction analyses (mutual information) were used to determine if the data were parameterized correctly. The entropy reduction analysis was also used to determine which input variables had the most influence on the endpoints, and therefore carried the most weight in determining risk to the endpoints. This sensitivity analysis was conducted within the Netica™ software program.

Entropy Reduction Analysis: Alternative Scenario- In addition to the entropy reduction analysis for the initial risk estimates, I created an alternative scenario to observe changes in the parameters that influence the risk to the endpoints. Fixed input nodes were not considered in the entropy analysis because only one possible state was available for these inputs and therefore changes could not be made in the nodes to reduce risk to the endpoints. In this alternative scenario, I gave each of the fixed states a distribution to see if these parameters were important considerations in the risk calculation.

Interactive Tools and Uses of Model

In addition to the sensitivity analysis, the model can also act as an interactive tool for managers and decision makers. Once such tool is back-calculating, where you set an endpoint value to a specific state (e.g. low) and observe changes throughout the model and back to the input nodes. This is a powerful tool for decision makers, especially when trying to optimize management strategies. This process can identify areas where management options would be most beneficial in reducing risk to the endpoints.

Total Risk Calculations

A Monte Carlo simulation was conducted to calculate the total risk to each endpoint (summing all four of the risk regions for each endpoint). The distributions from the endpoint nodes in the BNs were used as input data for the Monte Carlo model. The Monte Carlo simulation was completed using Crystal Ball Oracle, Fusion Edition software (version 11.1.2.3.000) as a macro in Microsoft Excel 2013. The simulation was run for 10,000 iterations, using the Latin Hypercube set at 500. The output figures display the distribution curves of the initial risk estimates and the risk after the management scenario was implemented for each of the seven endpoints, allowing for comparison of these two scenarios.

RESULTS

Risk by Regions: Initial Risk Estimate

The introduction of NIS was associated with risks (the Zero, Low, Medium and High states) and benefits (the Benefits state). The risk, defined as the probability of an undesirable effect to an endpoint determined by society to be important (Hines and Landis 2014), included introduction of diseases to the native species, population declines due to competition and predation by the NIS, and changes to the habitat. The benefits included additional food and shelter for the native species from the NIS introductions.

Region 4 (March Point) was the region with the highest risk. The distributions in this region had the highest probabilities in the medium and high states (compare Figure 8 and Supplementary Figures 1-3). Region 3, the Southern Region, had similar distribution patterns as Region 4; however, the probabilities were slightly shifted to the lower states due to moderate eradication of the NIS, *Spartina spp*. (Figure 8). Region 1 and 2 had similar distributions and risk scores. The risk score is the number located at the bottom of each node. The risk score is the mean value of the distributions of states for each node. Each state is assigned a value, Benefits -2, Zero 0, Low +2, Medium +4 and High +6, these numbers are weighted based on the distributions and combined to provide the risk score. The distributions of risk were shifted to the lower states (zero and low states) in Regions 1 and 2 compared to the results from Regions 3 and 4 (Figure 9-11).

Risk by Endpoints: Initial Risk Estimate

The changes in community composition endpoint had the greatest risk associated with it. The distribution was skewed to the bottom of the node, mostly to the medium and high states, and combined represented 67 to 74% of the probability of impacts occurring (Figure 9). The eelgrass and Dungeness crab endpoints also had distributions that were skewed towards the bottom, with the medium and high states corresponding to 55 to 64% of the total probability of risk (Figure 9). The eelgrass had higher risk scores across the four regions, but the Dungeness crab had a higher probability of risk distributed in the high state (Figures 9). These conflicting results were likely because the eelgrass endpoint had no benefits associated with it and the risk was distributed between four states instead of the five states of the Dungeness crab.

The water quality, juvenile salmon, and birds endpoints had similar distributions. These endpoints had a fairly equal distribution between the zero, low, and medium states, each with about 20-28% of the probability of risk associated with them (Figure 10). The harbor seal endpoint had the lowest risk in every region. Most of the risk, 75-80%, was distributed in the zero and low states (Figure 11).

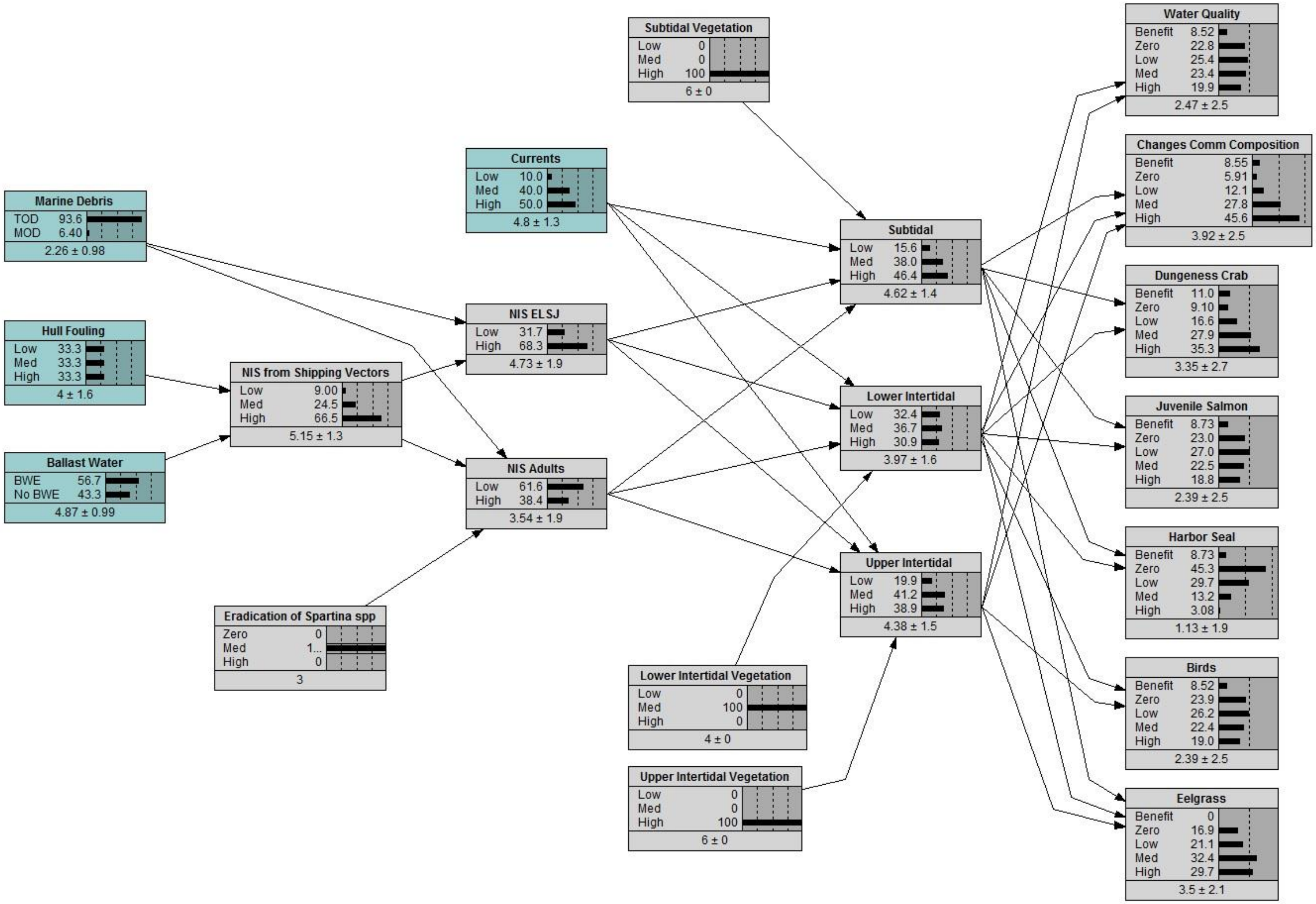

Figure 8. Bayesian model depicting the initial risk estimate from NIS introductions to Padilla Bay, Region 3. The teal nodes represent the vectors of NIS introduction. The vertical dashed lines in the nodes represent quartiles. One dashed line represents the 25% quartile, two dashed lines represent the 25 and 50% quartiles, and three dashed lines indicate the 25, 50 and 75% quartiles. The values at the bottom of each node represent the risk score, which is the mean of the distributions (black bars).

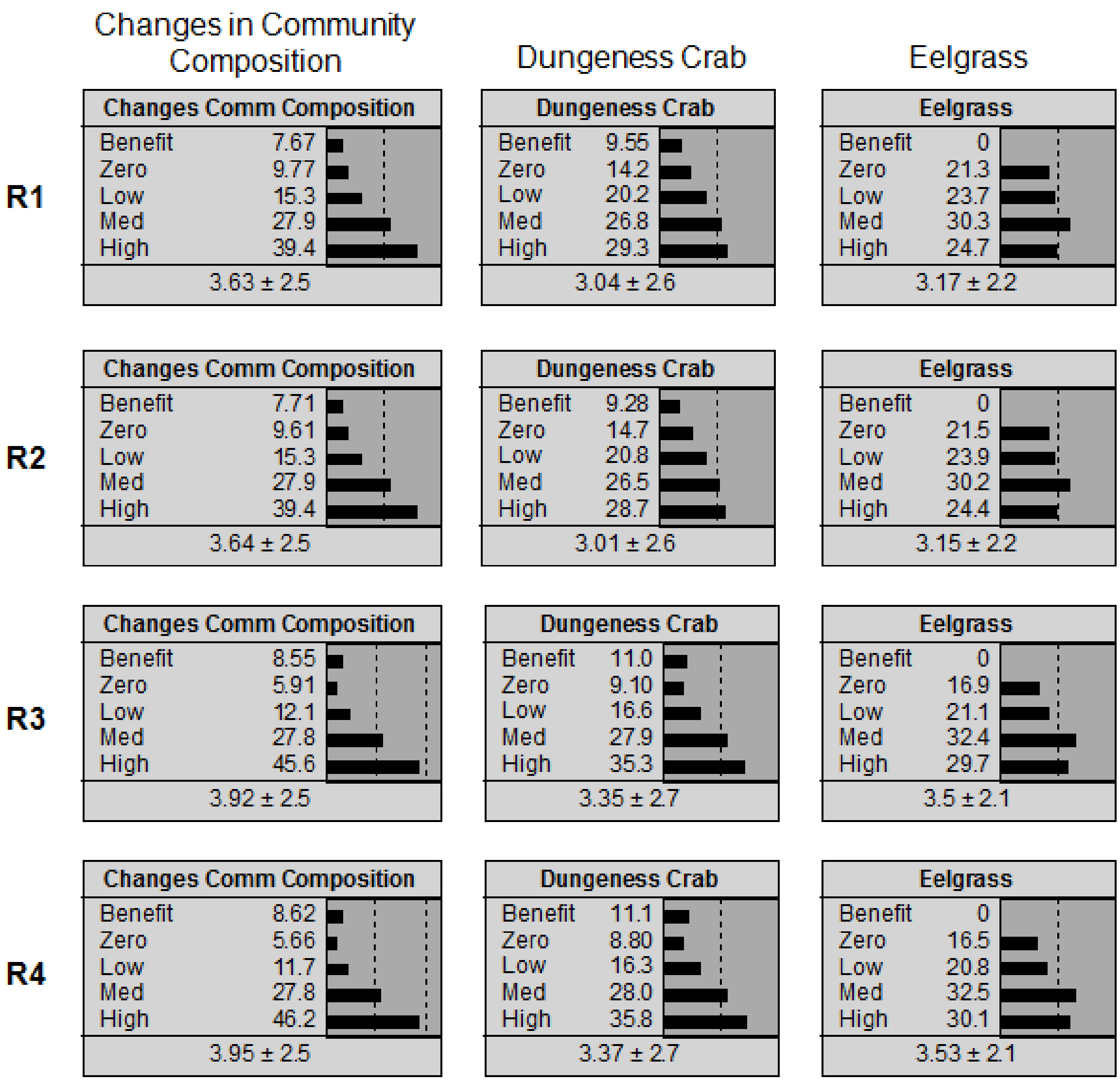

Figure 9. Distributions for the endpoints with the highest risk: Changes in Community Composition, Dungeness Crab, and Eelgrass. The four regions are presented: R1 – North, R2 – Mid, R3 – South, R4 – March Point. The vertical dashed lines in the nodes represent quartiles. One dashed line represents the 25% quartile, and two dashed lines represent the 25 and 50% quartiles. The values at the bottom of each node represent the risk score, which is the mean of the distributions (black bars).

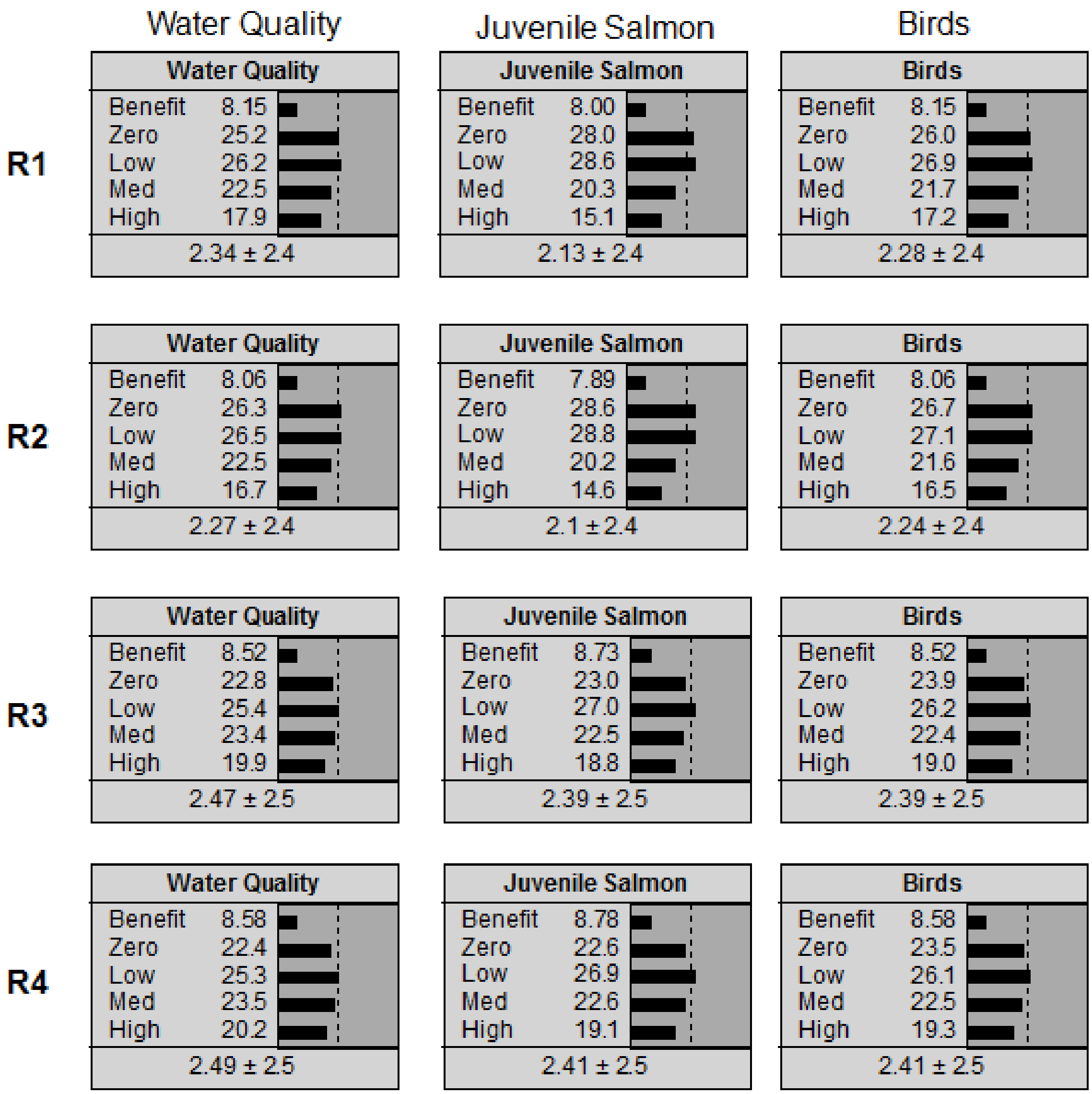

Figure 10. Distributions for the endpoints with moderate risk: Water Quality, Juvenile Salmon, and Birds. These endpoints had similar distributions and risk scores. The four regions are presented: R1 – North, R2 – Mid, R3 – South, R4 – March Point. The vertical dashed lines in the nodes represent quartiles. The one dashed line represents the 25% quartile. The values at the bottom of each node represent the risk score, which is the mean of the distributions (black bars).

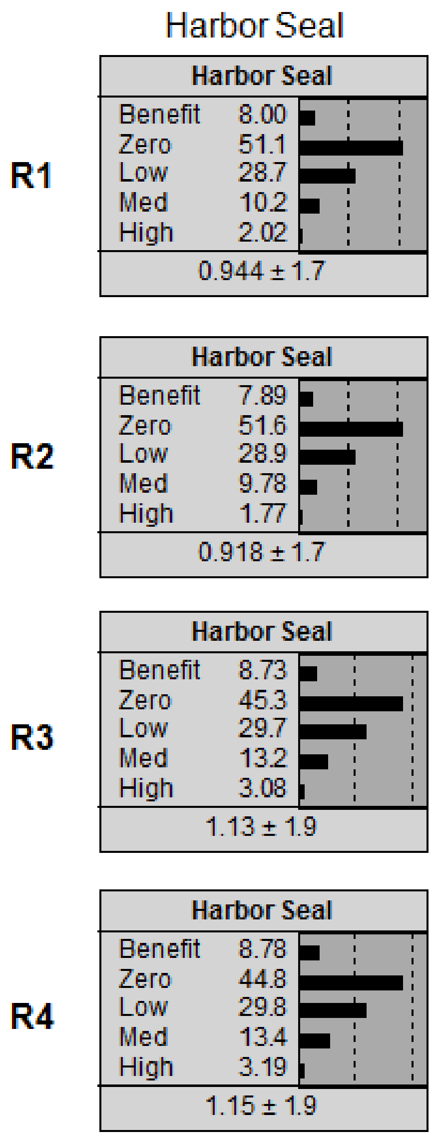

Figure 11. Distributions for the endpoint with the lowest risk: Harbor Seal. The four regions are presented: R1 – North, R2 – Mid, R3 – South, R4 – March Point. The vertical dashed lines in the nodes represent quartiles. Two dashed lines represent the 25 and 50% quartiles. The values at the bottom of each node represent the risk score, which is the mean of the distributions (black bars).

The distribution for the benefits state was similar across the endpoints (~8-11%), with the exception of the Eelgrass endpoint, which had no benefits from NIS introductions. The Dungeness crab had the greatest benefits from NIS introductions (Figure 9).

Risk after Management Scenario

The implementation of the management scenario (ballast water treatments) produced little change in the distributions. There was a slight shift (~1%) in risk from the high states to the zero and low states (Figures 12 and 13; Supplementary Figures 4-6). This scenario portrayed the highest risk reduction based on meeting the Phase I Standards set by the USCG.

Sensitivity and Uncertainty Analysis: Entropy Reduction Analysis

The entropy reduction analysis identified the input parameters with the greatest influence on the endpoints. The top entropy reduction input parameter for all endpoints (across all regions) was the *Currents* node, followed by *Marine Debris* and *Hull Fouling* nodes (Figure 14; Supplementary Table 4). An analysis was completed in which these input parameters were set to 100% at the lowest state. The risk scores for each endpoint were recorded and risk reductions calculated to determine the percent reduction of risk that would be obtained if management targeted these input nodes. The *Currents* had the largest risk reduction, which resulted in about a 10-25% reduction of risk to the endpoints. *Hull Fouling* reductions were the next greatest, with a 2-5% reduction of risk, followed by the *Marine Debris* input parameter with a ~1% reduction of risk (Supplementary Table 5). There was only a small reduction of risk from the *Marine Debris* node because the majority of the probability (weight) in this node was already set at the low state (93% in the TOD state, which was equivalent to the low state).

Entropy Reduction Analysis: Alternative Scenario- An alternative scenario was created to observe how the entropy reduction results changed when the fixed nodes (vegetative cover nodes) were given distributions. When I assigned a 20% probability to the states that were previously 0% and 60% to the state that was previously 100%, the habitat vegetation nodes were listed above the marine debris and hull fouling parameters in the entropy analysis. These parameters were then set to the lowest state and the percent change in risk scores was calculated. Currents remained the top input

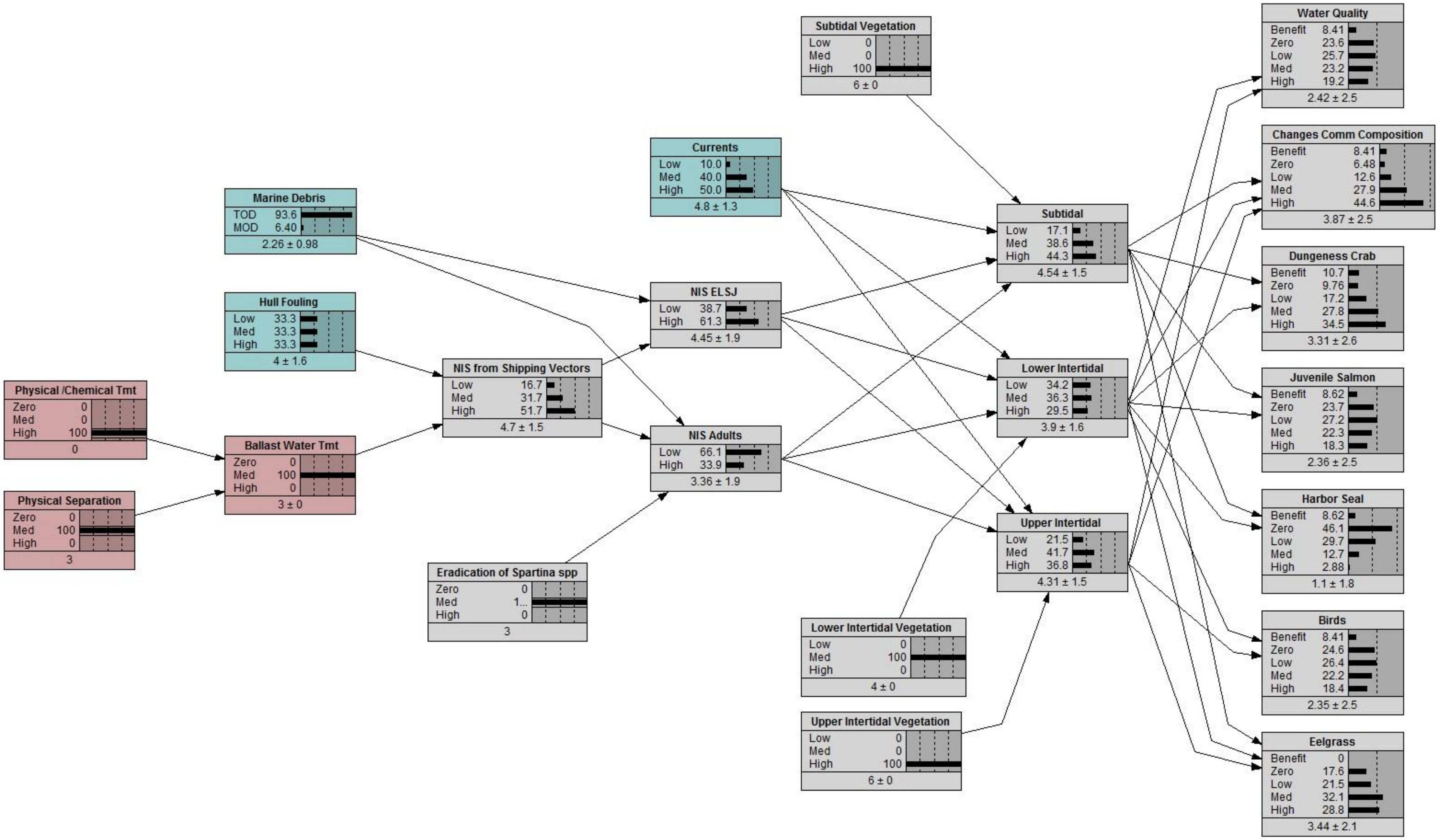

Figure 12. Bayesian model illustrating the probability of NIS introductions to Padilla Bay with the implementation of a ballast water management scenario, Region 3. The teal nodes represent the vectors of NIS introduction and the red-brown nodes represent the ballast water management treatments. The vertical dashed lines in the nodes represent quartiles. One dashed line represents the 25% quartile, two dashed lines represent the 25 and 50% quartiles, and three dashed lines indicate the 25, 50 and 75% quartiles. The values at the bottom of each node represent the risk score, which is the mean of the distributions (black bars).

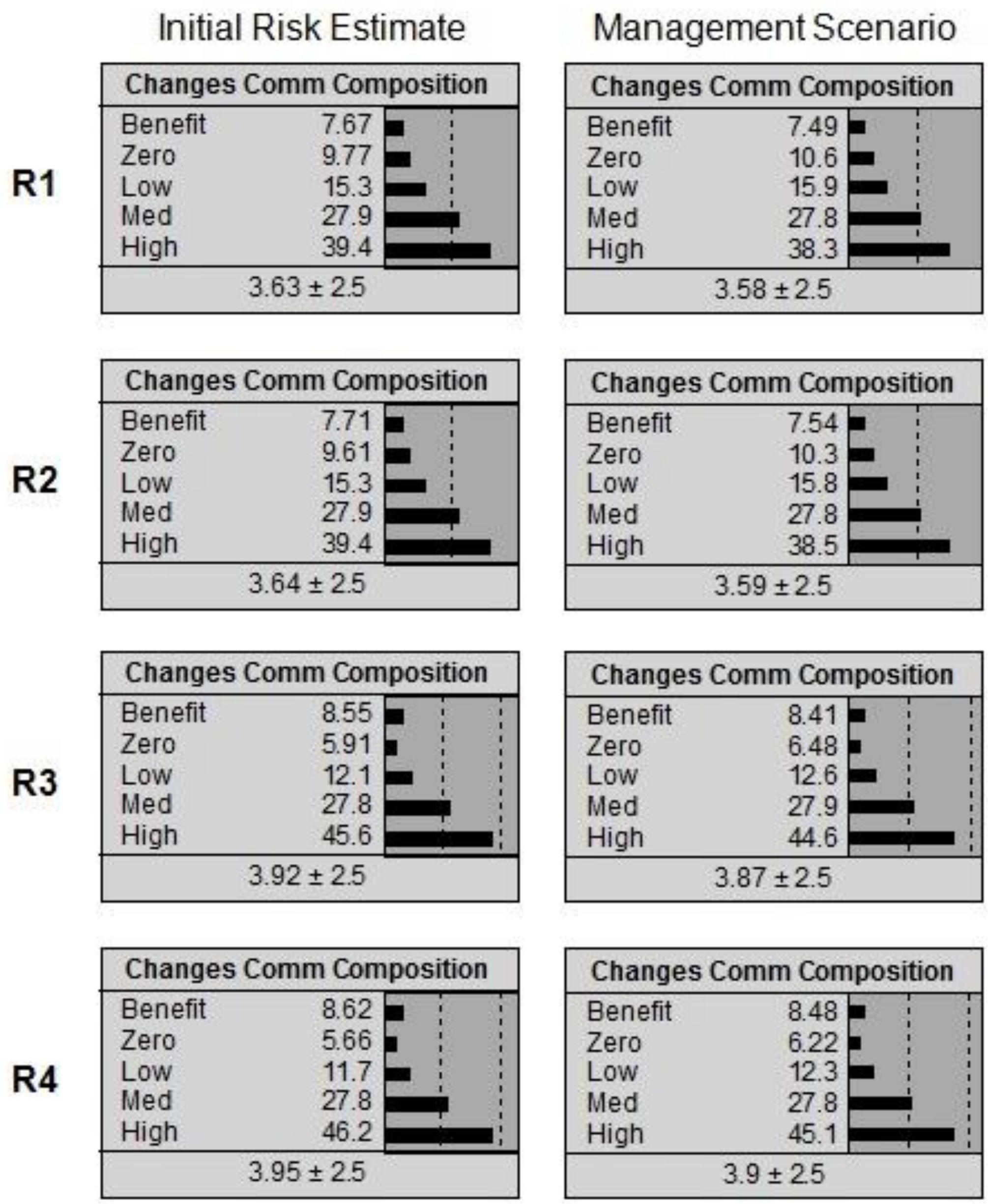

Figure 13. Risk comparison for the initial risk estimate (left) and the management scenario (right). The changes in community composition endpoint had the greatest change in the distributions, with a shift in risk of only around 1%. The four regions are presented: R1 – North, R2 – Mid, R3 – South, R4 – March Point. The vertical dashed lines in the nodes represent quartiles. One dashed line represents the 25% quartile, and two dashed lines represent the 25 and 50% quartiles. The values at the bottom of each node represent the risk score, which is the mean of the distributions (black bars).

parameter, with a 10-25% decrease in risk scores. The *Subtidal Vegetation* displayed a 4-12% decrease in risk scores, and the *Lower* and *Upper Intertidal Vegetation* nodes each had a 3-8% decrease in risk scores. The *Marine Debris* and *Hull Fouling* nodes had ≤1% and 1.8-4.5% decrease in risk scores, respectively.

Many of the input parameters were at the bottom of the entropy results list. The further away a node was from the endpoints, the less influence it had on the endpoint. If all nodes were analyzed in the entropy analysis, the top parameters included the habitats and other endpoints. The parameters that had the most impact on the endpoints were habitats the specific endpoint lives in and other organisms they interact with. This importance of interactions indicated that a small change in a community could have repercussions at many levels of the community.

The entropy reduction analysis also provided insight to errors in the input tables or CPTs. One such error that I encountered and immediately corrected occurred in the *Currents* node. Upon realizing that the fixed input variables were not included in the entropy reduction analysis, I re-analyzed the fixed nodes to confirm that they should indeed be fixed. This was true of all the nodes except the *Currents* node. There was uncertainty associated with the currents entering the bay that needed to be denoted in the input values of the *Currents* node. Therefore, this node could not be fixed and was changed to represent a probability of exposure across the three states (low, medium, and high).

Interactive Tools and Uses of Model

When I implemented back-calculations for a number of endpoints (set at the low state), the parameters that changed the most were the habitats (shift from higher states to the medium and low states), currents (shift to low exposure), and stressors (the specific life stages of the NIS). For both stages, the ELSJ and adults, there was a greater shift from the high to low states. While there is a need for reduction of the NIS stressors, the actual nodes depicting sources of stressors, *Ballast Water*, *Hull Fouling* and *Marine Debris* nodes, shifted only a few percent and the distribution patterns showed little change. This indicates there is not one easy solution or simple fix. Instead, multiple treatment efforts would need to be implemented to reduce the risk to the endpoints to achieve a level acceptable to the stakeholders and decision makers.

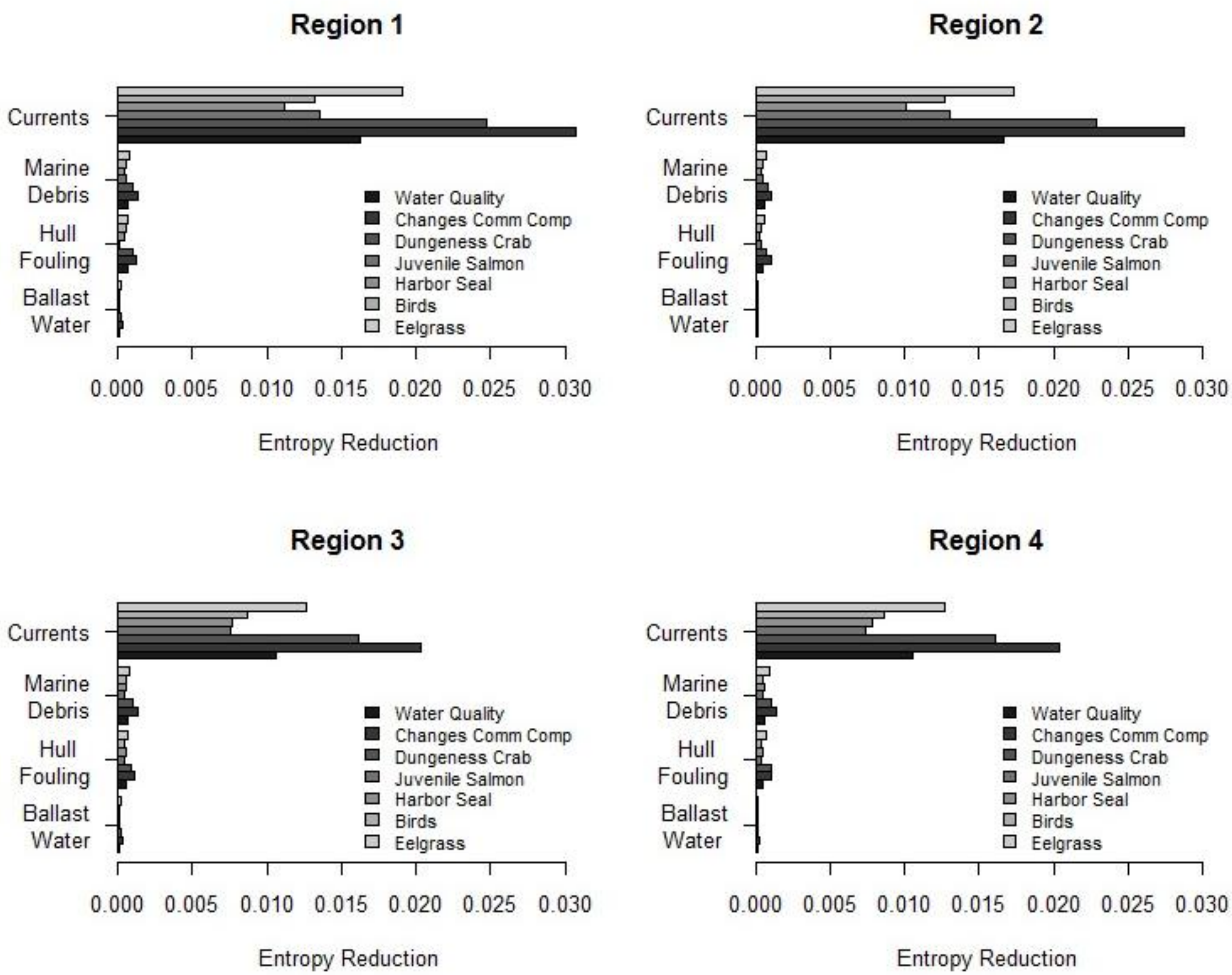

Figure 14. Entropy reduction results (mutual information) for the top input parameters. Figure created in R.

Total Risk Calculations

The Monte Carlo simulation displayed little change in risk to the endpoints when the management scenario was implemented. The curves for both the initial risk estimate and the management scenario overlap greatly indicating little reduction in the risk with the management scenario (Figure 15 A-E). The Monte Carlo simulation illustrated that the endpoints had different curves, representing varying distributions of risk. Juvenile salmon, birds, and water quality endpoints had normal (bell curve) distributions, whereas the harbor seal was skewed to the left (lower risk) and Dungeness crab and changes in community composition were skewed to the right (higher risk) (Figure 15 A, C, and D). These results were similar to the BN findings for each endpoint and across all regions. Juvenile salmon, birds, and harbor seal endpoints had more probability of benefits than the other endpoints, as depicted by their curves (Figure 15 B, C, and E).

DISCUSSION

Patterns of Risk

The greatest risk from NIS introductions was to the southern portion of Padilla Bay and March Point, Regions 3 and 4. These regions had the lowest percentages of vegetative cover and greatest exposure to currents (Bulthuis and Conrad 1995a,b). Low vegetative cover from various types of habitat disturbance, runoff from adjacent land use, and reduced species biodiversity increase the available habitat for NIS to settle and establish (Didham et al. 2005). Portions of Region 3 underwent mechanical and chemical eradication to remove the cordgrass, *Spartina spp*. The eradication process reduced the initial cordgrass population via mechanical mowing and chemical application (Rodeo®, active ingredient glyphosate) (Riggs 2011). Historical disturbances occurred in Region 3 during the 1930s to 1950s, when the southern portion of the bay was the site of extensive Japanese oyster culture (Dinnel 2000). These disturbances could have contributed to the habitat disturbance to this portion of the bay.

Of the seven endpoints considered in this BN-RRM, the changes in community composition, eelgrass, and Dungeness crab were most at risk from NIS introductions and impacts. The Dungeness

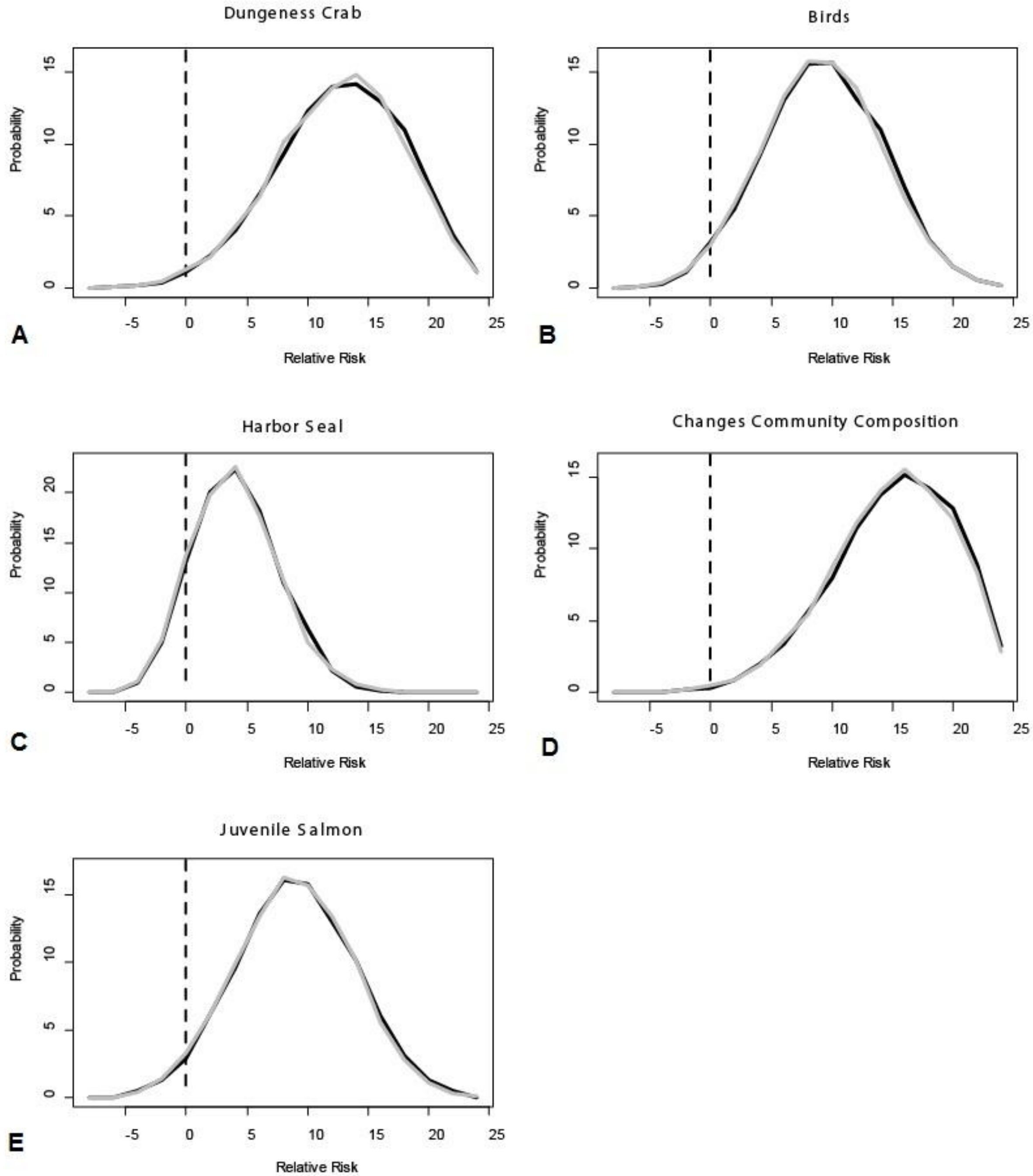

Figure 15. Monte Carlo risk comparison of the initial risk estimates and management scenario for five endpoints (all risk regions summed). The distributions represent the probabilistic risk for the initial risk estimates and the management scenario. The black line represents the initial risk estimates and the gray line represents the risk with the implementation of ballast water treatments. The dashed line at Zero Relative Risk separates the benefits (negative numbers) and the risk (positive numbers) associated with the NIS introductions. The Monte Carlo simulation was run for 10,000 iterations using the Crystal Ball Oracle, Fusion Edition software (version 11.1.2.3.000) as a macro in Microsoft Excel 2013. Figures created in R.

crab and eelgrass endpoints remain in the habitat the longest (year round for eelgrass and juvenile Dungeness crabs). The changes in community composition was also an endpoint affected year round, whereas most of the other endpoints only remained in the bay for a few months (e.g. juvenile salmon and many of the bird species), or used the bay sporadically, such as the harbor seal endpoint (Jeffrey 1976, Phillips 1984, Pauley et al. 1988, Bonar et al. 1989, PBNERR 2008).

The entropy reduction analysis indicated that *Currents* node was the input parameter that had the greatest influence on risk to the endpoints. The currents are the exposure route of NIS to the bay, as well as a vector transporting NIS from patches in adjacent bays to Padilla Bay. We can think about the transport of NIS via currents at many spatial scales, such as the local movement of water from the March Point and Anacortes ports (small scale) with NIS introductions coming from hull fouling or ballast water. At regional scales, currents transport NIS from other established patches in the Salish Sea or west coast of North America, such as the movement of the European Green crab (Colnar and Landis 2007). Currents can also transport NIS from a much larger scale with the movement of marine debris worldwide (JTMD 2012). The entropy results (currents having the greatest influence on the endpoints) convey the importance of patch-dynamics and the beachhead effect (Deines et al. 2005) and contemplating the spatial scales in NIS risk assessments (Colnar and Landis 2007).

Management Scenario

Building on the initial risk model, I was able to implement a management scenario to calculate risk reductions to the endpoints. When the ballast water management scenario was run, little reduction of risk occurred and the distribution patterns remained unchanged to the Padilla Bay endpoints. When experimenting with the models and inputting 100% reduction of propagules for all of the management nodes (highest level of reduction possible), the risk scores and distributions hardly changed. This is not to say that the ballast water treatments are ineffective. In fact, the model illustrated a reduction of propagule pressure as seen by the distributions from the initial risk estimate of the *NIS from Shipping Vectors* node that shifted from 66.5% in the high state to 51.7% in the high state in the management scenario (Figures 8 and 12). However, reductions of propagules from the management treatment did not have a substantial effect on the endpoints. Ballast water was only one vector of introduction and currents may be transporting NIS to the bay from a number of pathways (e.g. hull fouling, ballast water, and marine debris).

The ballast water treatments can also create additional sources of stressors that should be considered in the modeling process. Ballast water treatments that utilize chlorine products need to ensure that the chlorine is completely deactivated or broken down before the water is discharged (Albert et al. 2010, Lloyd's Register 2010). Deoxygenation treatments eliminate oxygen in the water, so the discharged water would have a lower concentration of dissolved oxygen that could affect the receiving community. All of the treatments may contribute to increased turbidity due to the backwashing of filters, flushing organisms and organic matter into the ports (Lloyd's Register 2010).

Using Risk Assessment in the Evaluation of Management Options

Though this study focused on Padilla Bay as a case study, the goal of the study was to demonstrate the BN-RRM approach can be successfully used to estimate risk from NIS introductions and impacts to endpoints in coastal regions. Ecological risk assessments using Bayesian networks have generally been used to analyze risk from contaminants (Ayre et al. 2014). This study illustrates that BNs can be constructed to evaluate risk from NIS introductions. Further, this model could be used as a template for NIS introductions in any body of water.

The findings of risk to Padilla Bay endpoints are likely not universal. If this approach were used in other areas, the results would differ based on the location, primary vectors of NIS introduction, history of the area, and the vicinity to other major ports. Many factors could affect the colonization of NIS, such as the geography of the region, the residence time of water in the bay, and the secondary transport of NIS (Cordell et al. 2009, Lawrence and Cordell 2010).

Effectiveness of the management options may depend on the type of pathways of introduction. Adjacent to Padilla Bay, the ports of March Point and Anacortes had 531 vessel arrivals over a three-year period (2011 to 2013). In comparison, Cherry Point, WA, had 465 vessel arrivals, Seattle/Tacoma had 5,255 vessel arrivals, the San Francisco Bay area had 6,705 vessels, and the major ports from the Great Lakes totaled 7,911 vessel arrivals over the same period (data from NBIC

2008). Many of the NIS already present in Padilla Bay were from historical aquaculture practices (Dinnel 2000) or currents transporting NIS from other bays or ports (PBNERR 2008). This site may have a lower risk from ballast water vectors than other ports, and a higher risk associated with exposure from other pathways of NIS. Managers utilizing this model may determine if it is more effective to manage species through eradication once a species has settled and colonized rather than trying to prevent NIS introductions.

Reduction of Uncertainty via Future Research Endeavors

Bayesian models can combine quantitative data and qualitative data (knowledge). This was essential in the creation of this model, where quantitative data were limited. In this risk assessment, there was much uncertainty, some that was due to limited quantitative data for the input frequencies and the ecological interactions described in the CPTs. Data limitations were encountered with the input parameters due to small sample sizes or a lack of statistically robust data (Ruiz and Smith 2005, Davidson et al. 2006). Quantitative data were missing for microorganisms associated with all vectors of introduction. In many instances, this was due to a lack of analytical tools to identify and detect microorganisms and viruses (California State Lands Commission 2013).

Uncertainty with hull fouling was due to a lack of input data (time since last dry-docking) so an equal distribution was assigned to each state in the node. In the future, when data are available, a number of parameters should be considered in addition to time since last dry-docking, to determine the probability of NIS introductions from hull fouling. These additional parameters include: speed of the vessel, port duration and residence time, frequency visiting the same port, and sailing route (Coutts and Taylor 2004, Ruiz and Smith 2005, Davidson et al. 2006, Sylvester and MacIsaac 2010, Sylvester et al. 2011). These parameters were not included due to the lack of data to distinguish between the various states (e.g. low, medium, and high). This was currently not an issue, but if I could improve the model and obtain hull fouling data, I would create a ranking scheme with all these parameters to provide the most reliable information for the introductions of NIS from hull fouling.

Many of the ballast water treatments are relatively new and still in the testing phase. Suppliers analyze and provide data for their own treatment systems and approval is given by the flag state, usually the country that the manufacturer originated from (Lloyd's Register 2010). Often, results describing the treatment efficacy were not made available to the public (only ~11-30% had some data available for the public) (Albert et al. 2010). Data that were made available were often missing quality assurance and quality control measures (Albert et al. 2010). In analyzing the performance of these ballast water treatments, some of the samples were not statistically robust. For instance, the propagule reduction results for the chlorine dioxide treatment (Echochlor) were based on only $3m^3$ of water (Gollasch 2011). Albert et al. (2010) and the USEPA SAB (2011) suggested that $30m^3$ to $60m^3$ of water were needed to represent the concentration of organisms in the total volume of ballast water. Lastly, the equipment needed to detect the smaller categories of organisms (≤10 μm) is not advanced enough to produce reliable results (California State Lands Commission 2013).

The results in the Padilla Bay case study are based on the best available data and current knowledge. The precision of this model would increase if we better understood the exposure of NIS from the various vectors of introduction and the ecological interactions of settling and colonizing by the NIS through patch dynamics and population models. In addition, the models would be more precise if the data were up-to-date. The GIS data (ESRI shape files of vegetative habitat of Padilla Bay from the SWMP Biomonitoring Pilot Site, 2004 (Bulthuis and Shull 2006)), used to determine the percent cover of vegetation throughout Padilla Bay were approximately 10 years old. Likewise, available currents data were about 20 years old and the movement of water into and out of Padilla Bay is not well understood, especially currents entering from the north (Doug Bulthuis, personal communication). Results and uncertainty from this model could change if these unknowns were further researched. Identifying the sources of uncertainty exemplifies where future studies should focus. The model could then be updated to reduce the uncertainty and provide a more precise estimate of the risk to the endpoints.

Conclusions

The ballast water treatments described here are only one type of management. Even if this treatment option was able to eliminate all organisms, there are still many other vectors of introduction, such as improper disposal of research or aquarium NIS (personal or commercial aquariums), aquaculture practices, the transport of live seafood or bait, hull fouling, marine debris, and movement of species due to warming waters.

The movement of species from climate change and shifts in water temperature should also be considered for future models. It is predicted that NIS distribution will expand north due to warming waters (Bossenbroek et al. 2005, Hellmann et al. 2008). These shifts could influence the biodiversity of organisms in communities and change the vectors of introduction with altered dispersal pathways that occur naturally or due to changes in shipping paths (Hellmann et al. 2008).

Additional management options may include educational awareness, such as encouraging the proper disposal of aquarium organisms and removal of marine debris. Much work needs to be done on this topic in the future; this risk assessment outlined some of the research needs for the vectors of introduction, community interactions, and management options.

The models presented in my thesis can be advantageous tools for determining the risk to endpoints from multiple vectors of NIS introductions to aquatic communities. This BN-RRM can be used as a template for NIS risk assessments and management in coastal areas in the Pacific Northwest and abroad, with slight changes to the model to represent the body of water and endpoints in question. With more research being conducted on the various vectors of introduction and more reliable data, updates to this model will make it more robust in determining the risk to Padilla Bay and other coastal locations.

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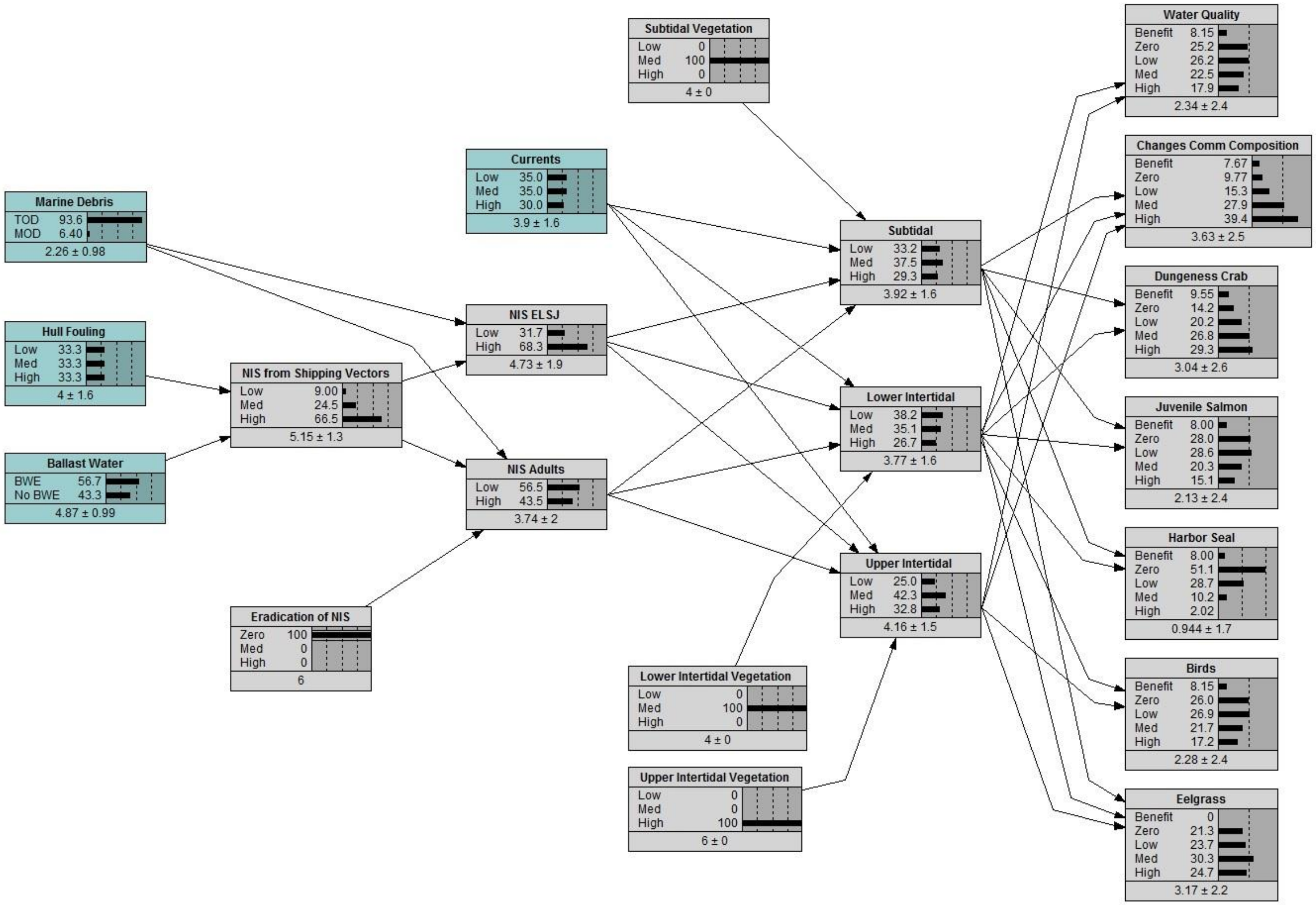
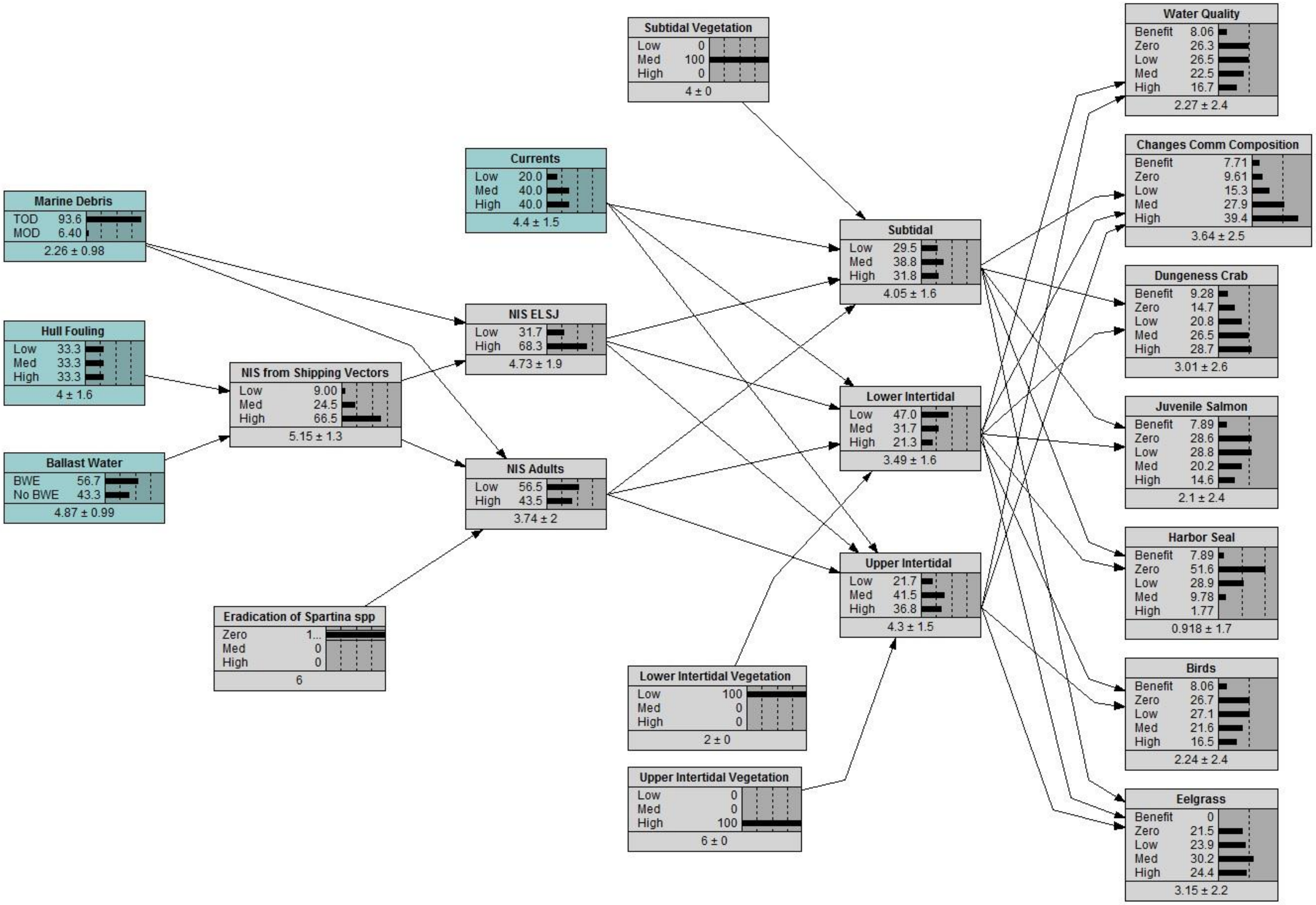
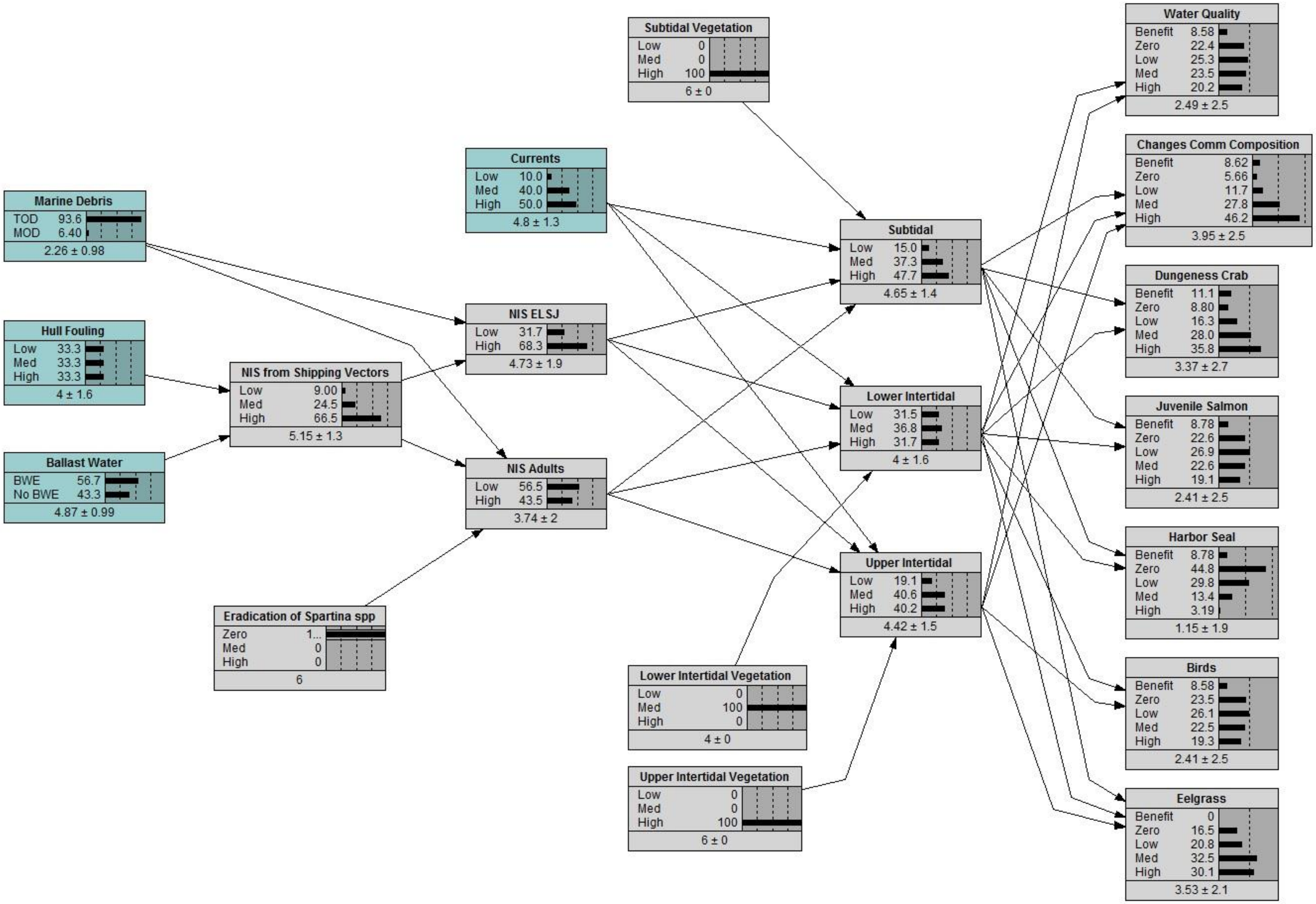
Supplementary Figures



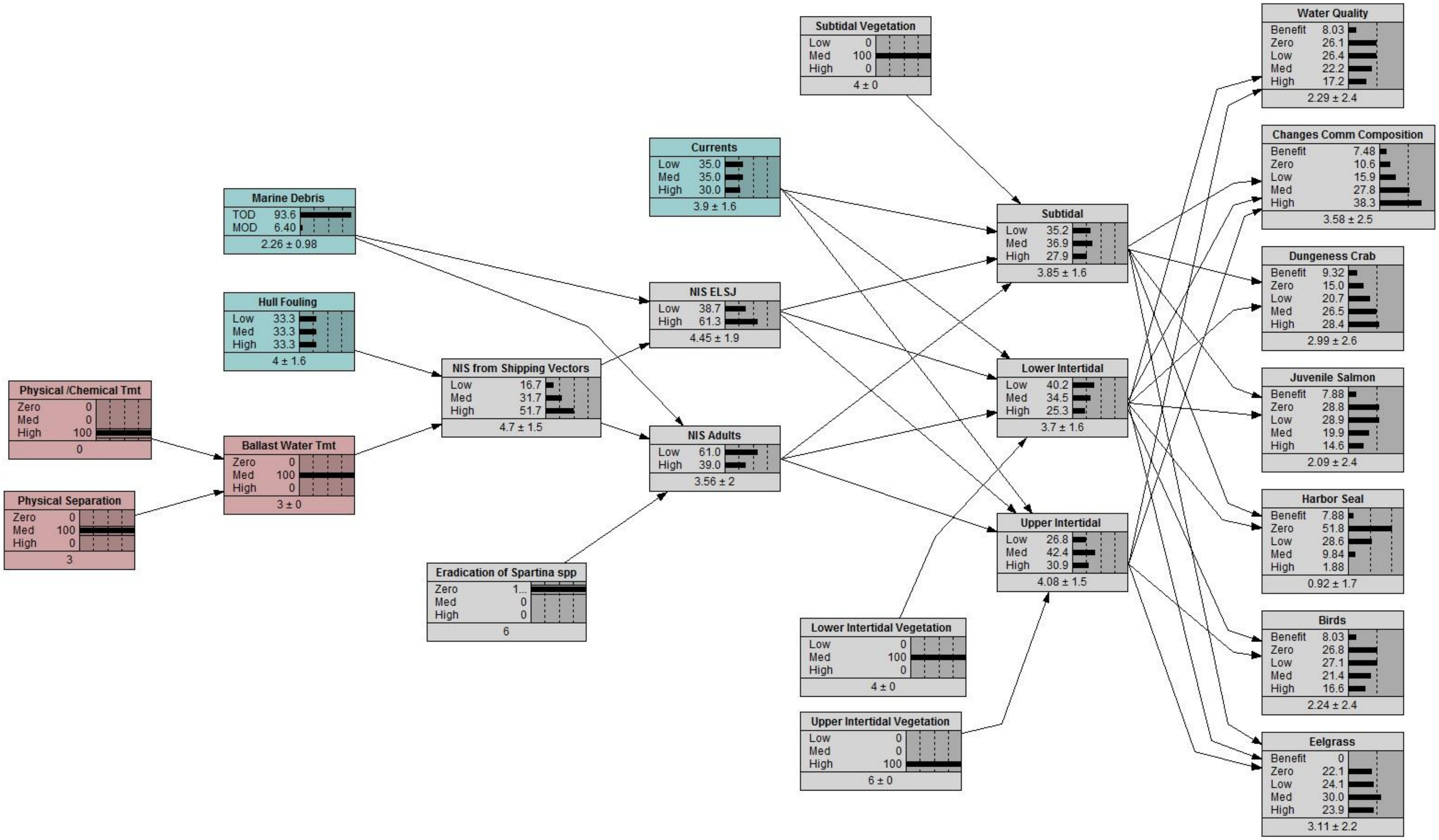
Supplementary Figure 1. Bayesian model depicting the initial risk estimates from NIS introductions to Padilla Bay, Region 1. The teal nodes represent the vectors of NIS introduction.



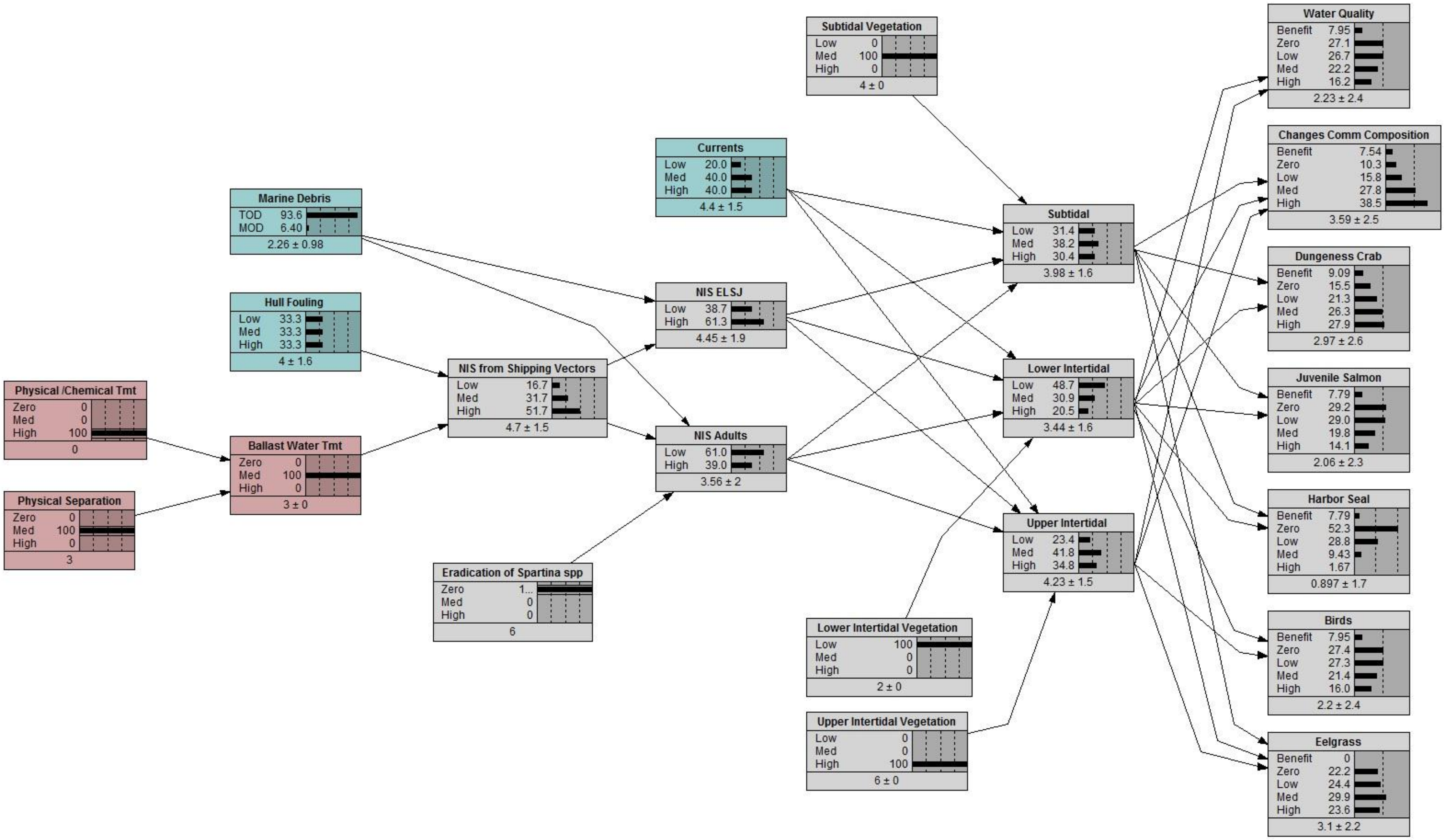
Supplementary Figure 2. Bayesian model depicting the initial risk estimate from NIS introductions to Padilla Bay, Region 2. The teal nodes represent the vectors of NIS introduction.



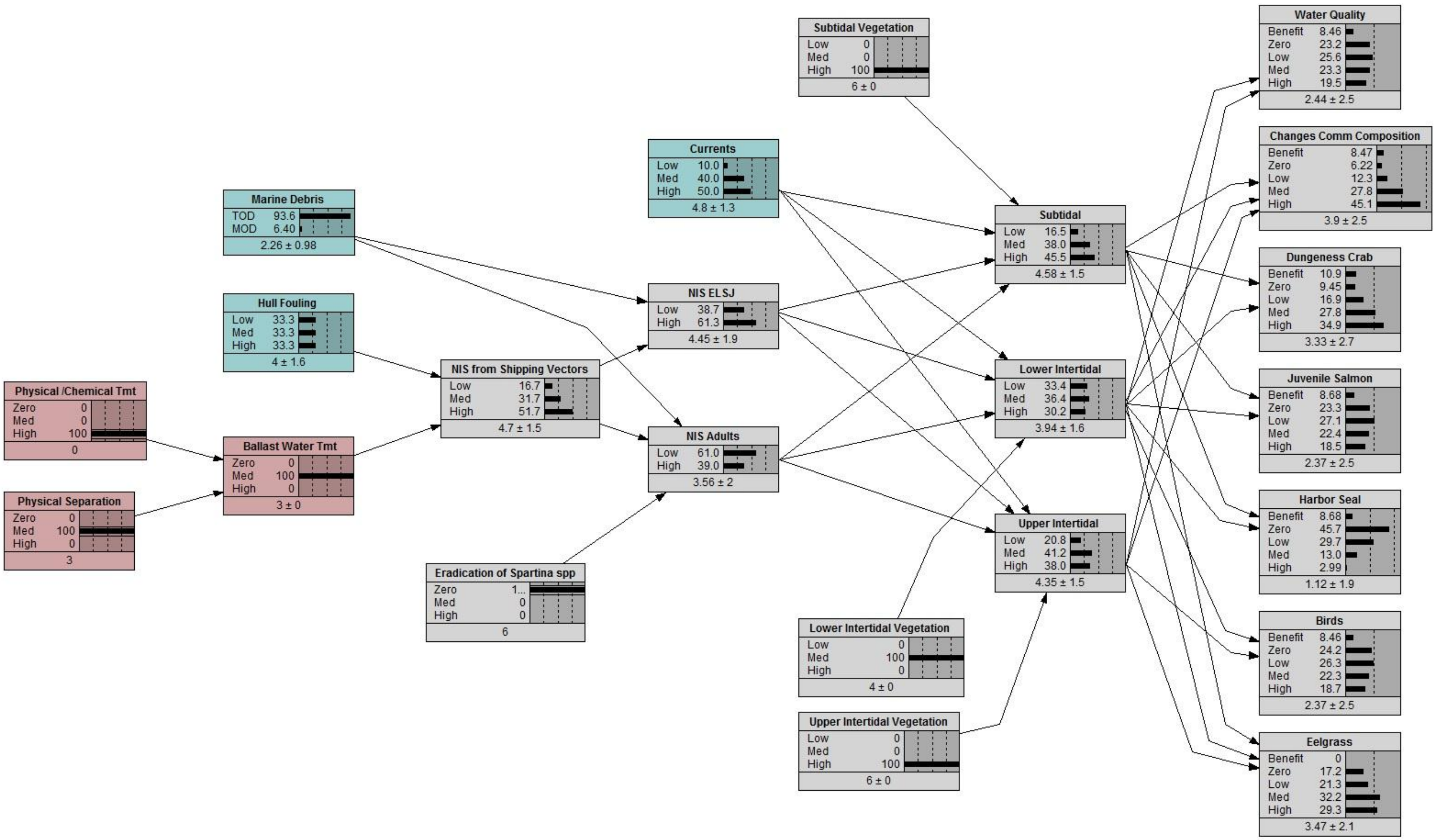
Supplementary Figure 3. Bayesian model depicting the initial risk estimate from NIS introductions to Padilla Bay, Region 4. The teal nodes represent the vectors of NIS introduction.



Supplementary Figure 4. Bayesian model illustrating the probability of NIS introductions to Padilla Bay with the implementation of a ballast water management scenario, Region 1. The teal nodes represent the vectors of NIS introduction and the red-brown nodes represent the ballast water management treatments.



Supplementary Figure 5. Bayesian model illustrating the probability of NIS introductions to Padilla Bay with the implementation of a ballast water management scenario, Region 2. The teal nodes represent the vectors of NIS introduction and the red-brown nodes represent the ballast water management treatments.



Supplementary Figure 6. Bayesian model illustrating the probability of NIS introductions to Padilla Bay with the implementation of a ballast water management scenario, Region 4. The teal nodes represent the vectors of NIS introduction and the red-brown nodes represent the ballast water management treatments.

Supplementary Tables

Supplementary Table 1. Model parameterization for all the nodes (input, child, and endpoint nodes) in the Bayesian model.

Model Variable & Definition	Variable State	Justification	References & Notes
Physical Separation[1]			
Reduction of propagules in ballast water due to Filtration Treatments	Zero <89.9% reduction	Ballast Water Exchange (BWE) can reduce propagules by 90%, therefore, successful ballast water treatment options need to have reduction rates of ≥90%	Minton et al. 2005 (State ranking & Justification; Albert et al. 2010, Lloyd's Register 2010 (Pathway)
	Medium 90-99.98% reduction	Filtration will prevent larger organisms from entering the ballast tanks (depending on filter size this may be >10μm or >25μm). Filtration is often paired with the other treatment options.	Albert et al. 2010, Lloyd's Register 2010 (Pathway & Justification)
	High >99.99% reduction	To pass the Phase I Standards, a reduction of 99.99% is required. High reduction will not be met with physical separation alone. Filtration is often paired with the other treatment options.	Albert et al. 2010, Lloyd's Register 2010 (Pathway & Justification)
Physical/ Chemical Treatment[1] (Biocidal Treatment or Physical Chemical Processes)			
Reduction of organisms in ballast water due to Biocidal Treatments (e.g. Chlorine Dioxide or Electrochlorination) or reduction of organisms due to Physical Chemical Processes (e.g. UV or UV + TiO_2)	Zero <89.9% reduction	BWE can reduce propagules by 90%, therefore, successful ballast water treatment options need to have reductions rates of ≥90%	Minton et al. 2005 (State ranking & Justification); Albert et al. 2010, Lloyd's Register 2010 (Pathway)
	Medium 90-99.98% reduction	Some vessels will pass the Phase I Standards with these reduction rates. At the lower bound (90%), vessels with <100 organisms/m^3 could pass the standards. At the upper bound (99.98%), vessels could pass the standards with up to 50,000 organisms/m^3. Passing these standards depends on the percentage of propagule reduction and the initial concentration of organisms in the ballast tanks.	Albert et al. 2010, Lloyd's Register 2010 (Pathway)
	High >99.99% reduction	The Phase I Standards state that fewer than 10 organisms/m^3 are allowed for the zooplankton category (≥50μm). Minton et al. (2005) found that may vessels have <3,000 organisms/m^3, but some of the ships had >50,000 organisms/m^3. In a distribution these ships would fit in the tails of the curve. To pass the Phase I Standards, a reduction of 99.99% is required.	Minton et al. 2005 (State ranking & Justification); Albert et al. 2010, Lloyd's Register 2010 (Pathway)
Ballast Water Tmt[1]			

Total reduction of propagules in ballast water from Physical Separation and Physical/ Chemical Treatments	Zero <89.9% reduction Medium 90-99.98% reduction High >99.99% reduction	The percent reduction categories were based off of the efficiency of ballast water exchanges and the Phase I Standards (see Physical Separation and Physical/ Chemical Treatment above). The CPT calculations were based off of passing or failing the Phase I Standards, which are regulations set by the USCG to reduce the probability of NIS introductions to coastal waters[2].	Minton et al. 2005, Albert et al. 2010, Lee et al. 2010, USEPA SAB (2011)
Ballast Water			
Mid-ocean ballast water exchange (BWE) from either empty-refill or flow through methods	BWE ≤90% reduction in propagules	Ballast water exchanges can result in a 90% reduction of zooplankton. To pass the Phase I Standards, this means that vessels can only have 100 organisms/m^3. Only about 17% of vessels will pass the Phase I standards with a BWE. Ballast water exchanges reduce coastal organisms in ballast tanks; however, many organisms (coastal and oceanic) are still discharged into the receiving port.	Minton et al. 2005
No ballast water exchange	No BWE No reduction of propagules	Discharge of ballast water without a BWE will likely only result in 4% of vessels passing the Phase I Standards.	Minton et al. 2005
Hull Fouling			
Organisms attached to the exterior of the vessel, on the hull, sea-chests, rudders, propellers, etc.	Low <14 months	Ships that have recently dry-docked have undergone hull maintenance (de-fouling of the hulls and applying anti-fouling paint). After 12-14 months, hulls remained relatively free of fouling.	Coutts and Taylor 2004, Sylvester et al. 2011 (pathway & classification of states) For the input values, an equal distribution (33.3%) was assigned to each state due to lack of data available for this vector
	Medium 14-36 months	Fouling of the hulls was observed after about 14 months after last dry dock.	
	High >36 months	Vessels that remained in the water for >36 months displayed more fouling of the hulls. Anti-fouling paint wears with time, becoming less effective. Vessels that have been in the water more than 3 years (36 months) are ready for dry-docking and re-application of anti-fouling paint (some ships dry-dock after 5 years).	
NIS from Shipping Vectors			
Total probability of	Low	Vessel has recently been dry-docked and hull maintenance	Coutts & Taylor 2004, Minton et

NIS introductions from shipping vectors (hull fouling and ballast water)		performed; ballast water has been treated before disposal in receiving port	al. 2005, Ruiz & Smith 2005, Davidson et al. 2009, Sylvester & MacIsaac 2010, Sylvester et al. 2011
	Medium	Vessel has recently been dry-docked and hull maintenance performed; ballast water was exchanged mid-ocean. Alternatively, vessel has not been dry-docked recently (>14 months); ballast water treated before disposal in receiving port	
	High	Vessel is due to be dry-docked and have hull maintenance performed; ballast water was not exchanged before disposal into receiving port	
Marine Debris			
Introduction of NIS from transport on Terrestrial Origin Debris (TOD)	TOD	TOD= Terrestrial-origin debris. This debris is washed into the water and carried with the currents. Colonization of this debris is mostly from pelagic (open ocean) organisms.	JTMD 2012 (classification of debris), Ocean Conservancy Reports 2012 & 2013 (data)
Introduction of NIS from transport on Marine Origin Debris (MOD)	MOD	MOD= Marine-origin debris. Items intentionally submerged in the water (buoys, floats, etc.). Biofouling of these items may occur over long periods of time. If detached, this debris becomes a possible vector of NIS to locations globally.	JTMD 2012 (classification of debris), Ocean Conservancy Reports 2012 & 2013 (data)
NIS Early Life Stages & Juveniles (NIS ELSJ)			
Probably of NIS introductions from early life stages or juvenile stages (ELSJ)	Low	Little probability of NIS organisms from shipping vectors (vessel recently dry-docked, ballast water treated); majority of marine debris from terrestrial origins instead of marine origins	Aliani and Molcard 2003, Masó et al. 2003, Davidson et al. 2006, Briski et al. 2011
	High	High probability of NIS from shipping vectors (vessel needs hull maintenance, ballast water not exchanged); marine debris from marine origins	
NIS Adults			
Probably of NIS introductions from adult stages/ organisms	Low	Little probability of NIS organisms from shipping vectors (vessel recently dry-docked); majority of marine debris from terrestrial origins instead of marine origins	Cohen et al. 1995, Aliani & Molcard 2003, Coutts et al. 2003, Coutts & Taylor 2004, Davidson et al. 2006, JTMD 2012
	High	High probability of NIS from shipping vectors (vessel needs hull maintenance); marine debris from marine origins	
Eradication of NIS			

Reduction of established NIS from chemical and/or mechanical actions	Zero <89.9%	No eradication practices were conducted or eradication actions were attempted, but no substantial reduction of the NIS population was observed. NIS will likely continue to survive unless additional treatments are implemented.	Dethier and Hacker 2004, Bossenbroek et al. 2005 (Justification), Sharon Riggs, Padilla Bay Reserve, personal communication
	Medium 90-99.98%	Chemical or mechanical actions reduce NIS to a small proportion of the original concentration of NIS, but complete eradication was not achieved.	
	High >99.99%	The high state equates to an almost complete eradication of the NIS species in question. Complete eradication is very difficult to accomplish, and very costly to implement.	
Currents			
Exposure of NIS to Padilla Bay from the Guemes Channel, Swinomish Channel, and the Strait of Georgia.	Low	Currents primarily from only one source. Low exposure of NIS to the region will result in a lower likelihood of NIS settlement and establishment.	Bulthuis and Conrad 1995 a, b (data & pathway), Landis and Wiegers 2005 (exposure overlap) The currents (exposure) changed with tidal fluxes, seasonal changes, etc. Uncertainty was associated with the currents due to incomplete knowledge of the movement of water flowing into Padilla Bay. This was reflected in the input distributions.
	Medium	Region receives currents from two of the three sources (e.g. Guemes Channel + Strait of Georgia). Greater overlap of exposure (of NIS) and the habitat results in a higher likelihood of NIS settlement and establishment.	
	High	Region receives currents from all three of the sources. High likelihood of NIS settlement and establishment will occur in regions with the most exposure of NIS.	
Subtidal Vegetation			
Percent cover of vegetation (*Z. marina*) in the subtidal habitat	Low (>66.7%)	High vegetative cover meant there was less space available for NIS to enter, settle and establish. Areas with higher vegetation had a higher biodiversity, which reduced likelihood of NIS invasions.	Phillips 1984 (pathway & justification), Andersen et al. 2004
	Medium (33.4-66.6%)	Medium percent cover of vegetation and biodiversity. Settlement and establishment could possibly occur in these areas.	Didham et al. 2005 (pathway & justification)
	High (<33.3%)	Low percent cover of vegetation and lower biodiversity increases available habitat and likelihood of NIS to settle, establish, and interact with the community.	
This is a fixed node. Percent cover of vegetation differs for each region: Region 1: 55.4%, Region 2: 38%, Region 3: 6.4%, Region 4: 28.2%			

Lower Intertidal Vegetation			
Percent cover of vegetation (*Z. marina*, macroalgae) in the lower intertidal habitat	Low (>66.7%)	See Subtidal Vegetation Justification and References above. This is a fixed node. Percent cover of vegetation differs for each region: Region 1: 58.2%, Region 2: 77.1%, Region 3: 47.3%, Region 4: 62.1%	
	Medium (33.4-66.6%)		
	High (<33.3%)		
Upper Intertidal Vegetation			
Percent cover of vegetation (*Z. marina*, *Z. japonica*, macroalgae, salt marshes) in the upper intertidal habitat	Low (>66.7%)	See Subtidal Vegetation Justification and References above. This is a fixed node. Percent cover of vegetation differs for each region: Region 1: 22.3%, Region 2: 11.3%, Region 3: 10.2%, Region 4: 4.0%	
	Medium (33.4-66.6%)		
	High (<33.3%)		
Subtidal			
Habitat for many endpoints	Low	High vegetative cover and biodiversity in the community; currents moving water away from Padilla Bay (ebbing tides)	Bulthuis & Conrad 1995a,b; Cohen et al. 1995, Ruiz et al. 2000, Deines et al. 2005, Landis & Wiegers 2005
	Medium	Moderate vegetative cover and biodiversity in the community; movement of water into the bay	
	High	Little vegetative cover in the subtidal zone and consequently, lower biodiversity in the community; currents moving water into bay	
Lower Intertidal			
Habitat for many endpoints	Low	High vegetative cover and biodiversity in the community; currents moving water away from Padilla Bay (ebbing tides)	Bulthuis & Conrad 1995a,b; Cohen et al. 1995, Ruiz et al. 2000, Deines et al. 2005, Landis & Wiegers 2005
	Medium	Moderate vegetative cover and biodiversity in the community; movement of water into the bay	
	High	Little vegetative cover in the lower intertidal zone and consequently, lower biodiversity in the community; currents moving water into bay	

Upper Intertidal			
Habitat for many endpoints	Low	High vegetative cover and biodiversity in the community; currents moving water away from Padilla Bay (ebbing tides)	Bulthuis & Conrad 1995a,b; Cohen et al. 1995, Ruiz et al. 2000, Deines et al. 2005, Landis & Wiegers 2005
	Medium	Moderate vegetative cover and biodiversity in the community; movement of water into the bay	
	High	Little vegetative cover in the subtidal zone and consequently, lower biodiversity in the community; currents moving water into bay	
Water Quality[4]			
Endpoint for the BN-RRM	Benefit	Additional filtration of water	Rippey 1994, Hallegraeff 1998, Harvell et al. 1999, Masó et al. 2003, Albert 2010, Landis et al. 2010, Lloyd's Register 2010
	Zero	No change to water quality in the bay	
	Low	Small impacts from NIS, such as slight decreases in DO, increased turbidity	
	Medium	Impacts from NIS including decreases in DO, increased turbidity, few episodes of disease or Harmful Algal Blooms (HAB)	
	High	Impacts from NIS including decreases in DO, increased turbidity, frequent episodes of diseases and/or HAB	
Changes to Community Composition[4]			
Endpoint for the BN-RRM	Benefit	Additional habitat	Thompson 1991, Cohen et al. 1995, Ray 2005, Wonham et al. 2005, Hacker & Dethier 2006, Bingham 2007, Colnar & Landis 2007, Wallentinus & Nyberg 2007, Bingham 2008
	Zero	No change in community composition/structure	
	Low	Small shifts if community composition/structure in isolated patches	
	Medium	Shifts if community composition/structure in larger patches	
	High	Regime shift in bay – physical and chemical structure of the bay distinctly altered; shift in species composition	
Dungeness Crab[4]			
Endpoint for the	Benefit	Additional habitat and food sources	Pauley et al. 1986, Fernandez et al. 1993,

BN-RRM (*Cancer magister*)	Zero	No change to Dungeness crab populations	Cohen et al. 1995, Colnar & Landis 2007
	Low	Slight competition or predation by NIS, may have patches of the bay without Dungeness crab	
	Medium	Decrease in Dungeness crab populations in patches throughout bay due to competition for resources, predation by NIS, diseases transported by NIS	
	High	Significant decreases in crab populations due to NIS interactions – this could lead to relocation of Dungeness crabs and/or local extinction	
Juvenile Salmon[4]			
Endpoint for the BN-RRM Pink salmon (*Oncorhynchus gorbuscha*) and Chum salmon (*Oncorhynchus keta*)	Benefit	Additional food source	Bailey et al. 1975, Jeffrey 1976, Pauley et al. 1988, Bonar et al. 1989, Ray 2005
	Zero	No change to juvenile salmon populations or livelihood in bay	
	Low	Some competition between juvenile salmon and NIS for resources	
	Medium	Competition between juvenile salmon and NIS for resources, salmon may have to change preferred diet for sustenance; predation by NIS	
	High	Competition between juvenile salmon and NIS for resources, salmon may have to change preferred diet for sustenance or relocate to different estuaries; predation by NIS	
Harbor Seal[4]			
Endpoint for the BN-RRM (*Phoca vitulina*)	Benefit	Additional food sources	Jeffrey 1976, Cohen et al. 1995, Hallegraeff 1998, Harvell et al. 1999, Colnar & Landis 2007, Gulland & Hall 2007, Padilla Bay NERR 2008, de la Riva 2009
	Zero	No change to Harbor Seal population	
	Low	Possible transfer of disease or HAB up food web	
	Medium	Episodic transfer of diseases or HAB up food web resulting in illness to Harbor Seal population	
	High	Frequent transfer of diseases or HAB up food web resulting in illness or death to Harbor Seal population	
Birds[3,4]			
Endpoint for the	Benefit	Additional food source	Jeffrey 1976, Liat & Pike 1980, Phillips

BN-RRM	Zero	No change to bird populations	1984, Ching 1989, Derksen & Ward 1993, Rippey 1994, Cohen et al. 1995, Newman et al. 2007, Padilla Bay NERR 2008, Vennesland & Butler 2011
	Low	Slight competition with NIS for food resources; few incidences of disease transfer via food web interactions	
	Medium	Competition with NIS for food resources; more frequent incidences of disease transfer via food web interactions, resulting in illness	
	High	Competition with NIS for food resources, birds may be forced to forage in other coastal habitats; frequent incidences of disease transfer via food web interactions, resulting in illness or death	
Eelgrass[4]			
Endpoint for the BN-RRM Native eelgrass (*Zostera marina*)	Benefit	No benefits from NIS to eelgrass	Phillips 1984, Muehlstein 1989, Garcias-Bonet et al. 2011
	Zero	No change in eelgrass densities in bay	
	Low	Slight reduction of eelgrass densities/coverage in intermittent patches due to competition or disease	
	Medium	Reduction of eelgrass densities/coverage in larger patches due to competition or disease, lower species diversity associated with these patches	
	High	Reduction of eelgrass densities/coverage in large portions of the bay due to competition or disease; lower species diversity and/or changes in species composition; available habitat for NIS to settle in	

[1]These parameters are in the ballast water management scenario models.

[2]Phase I Standards are listed for six categories of organisms: <10 organisms/m^3 that are ≥50µm in size, <10 organisms/ml that are <50µm but ≥10µm in size, Bacteria (*Vibrio cholera* <1 CFU per 100ml, *E. coli* < 250 CFU per 100ml, *Interestinal enterococci* <100 CFU per 100ml), and Viruses (no limitations at this time) (Lee et al. 2010, Albert et al. 2010, USEPA SAB (2011)).

[3]Great Blue Heron (*Ardea herodias*), Black Brant (*Branta bernicla nigricans*), Diving ducks (e.g. Surf Scoters, Black Scoters, White-Winged Scoters) and Dabbling ducks (e.g. Pintail, Green-Winged Teal, Mallards) are the birds represented by this endpoint.

[4]Published literature was used to derive a ranking scheme to combine multiple effects from NIS introductions and colonization. These calculations were used with the interactions in the habitats to distinguish the probability of each state occurring in the endpoint CPTs. Benefits from NIS include additional food sources and shelter, whereas the risk includes disease, reduction of native species populations due to competition and predation, etc.

Supplementary Table 2. Ranking scheme and calculations for Endpoints. These scores were used as a way to objectively analyze risk to each endpoint considering all of the possible effects listed below. The scores do not necessarily represent the risk found in Padilla Bay, but rather are a tool to aid in completing the CPTs. A literary search was completed on the native species for the following categories: Diseases/Biotoxins, Predation, Competition, and Length of Time Spent in the Habitat. Characteristics of some of the most well known NIS were also researched and combined all of this data to create a more complete picture of plausible effects from NIS invasions events to the endpoints. The Water Quality and Changes in Community Composition endpoints have slightly different effects: Dissolved Oxygen (DO), Turbidity, Changes to Sediment Composition, Chemistry, and Physical Structure of the Habitat. They are separated into individual tables (below). It should also be noted that there are possible benefits or gains from the introduction of NIS, such as increased food sources and construction of additional habitats.

The tables below consist of multiple parts. Part (**A**) describes the rankings I assigned each of the possible NIS effects. I then used the scores from (**A**) to quantify risk from the combination of effects for each endpoint (**C**). A total rank was calculated for each combination and then I matched the total risk from (**C**) to the Ranking Scheme and CPT Distribution Patterns in (**B**). The CPT Distribution Patterns were simply a way to analyze overall risk, for instance, Skewed Right meant that there was high risk associated with the combination of effects. These risk scores created patterns that allowed me to fill out the CPTs to reflect the basic shape of the risk described. The ranks I assigned in part (**C**) were based on scientific findings, references of which can be found in the model parameterization table (Supplementary Table 1).

A

	Effects					**Length of Time Spent in Habitat**		
Description of Risk	No Effect	Possible Loss/ Impact*	Probable Loss/ Impact**	Probable Benefit		Low 0-4 Months	Medium 4-8 Months	High 8-12 Months
Rank	1	2	4	0.75		1	2	4

*Possible impact or loss: In this scenario, there may not be site-specific data available, or the cause and effect pathways were determined by combining evidence from multiple literature sources. For instance, birds may acquire the disease *Salmonella spp*. Shellfish are a host of the disease *Salmonella spp*. Diving ducks eat shellfish, thus it is possible that these ducks could acquire *Salmonella spp.* from eating NIS shellfish. This is not a direct link, but all the pieces fit together to create a plausible pathway. However, there is more uncertainty associated with this causal pathway so a score of 2 would be given.

**Probable Loss or Impact: Literature provides evidence supporting 'loss' or impact.

B

Total Rank	**Ranking Scheme**	**CPT Distribution Pattern**
128-256	High	Skewed Right
64-128	High	Skewed Right
32-64	Med-High	Middle To Right
16-32	Medium	Middle
8 - 16	Low-Med	Middle To Left
<8	Low	Skewed Left

C

Endpoint	Length of Time in Habitat	"Losses"			"Benefits"		Total Rank
		Disease/ Biotoxins[1]	Predation	Competition	Food Source	Creating Habitat	
Dungeness Crab	4	2	4	4	0.75	0.75	**72**
Juvenile Salmon	2	2	1	4	0.75	1	**12**
Harbor Seal	1	2	1	2	0.75	1	**3**
Birds	2	4	1	2	0.75	1	**12**
Eelgrass	4	2	1	2	1	1	**16**
Max Possible Score	**4**	**4**	**4**	**4**	**1**	**1**	**256**

Endpoint	Length of Time in Habitat	"Losses"			"Benefits"	Total Rank
		Disease, Biotoxins[1], Bacteria	DO	Turbidity	Filtering Water	
Water Quality	4	4	1	2	0.75	**24**
Max Possible Score	**4**	**4**	**4**	**4**	**1**	**256**

Endpoint	Length of Time in Habitat	"Losses"			"Benefits"	Total Rank
		Disease	Changes In Sediment Composition & Chemistry	Changes In Physical Structure Of Habitat	Creating Habitat	
Changes in Community Composition	4	4	4	4	0.75	**192**
Max Possible Score	**4**	**4**	**4**	**4**	**1**	**256**

Supplementary Table 3. Conditional Probability Table (CPT) for the Ballast Water Management Treatment options. This example shows the calculations for the CPT for the *Ballast Water Treatment* node. Note: a high reduction of Physical Separation is unlikely to be met due to limitations in filtration size.

Ballast Water Treatment - CPT				
Physical Separation	**Physical Chemical Processes**	**Zero** 0-89.9%	**Moderate** 90-99.98%	**High** 99.99-100%
Zero	Zero	100	0	0
Zero	Moderate	100	0	0
Zero	High	100	0	0
Moderate	Zero	100	0	0
Moderate	Moderate	45	55	0
Moderate	High	0	100	0
High	Zero	100	0	0
High	Moderate	0	100	0
High	High	0	50	50

Calculations for the table below:

*Split between the Zero and Moderate State

89.9 – 81.0 = 8.9
99.96 – 89.9 = 10.06

99.96 – 81.0 = 18.96

(8.9/18.96) * 100 = 46.9% (estimated/rounded value to 45)
(10.06/18.96) * 100 = 53.1% (estimated/rounded value to 55)

**Split between the Moderate and High State

99.99 – 99.98 = 0.01
100 – 99.99 = 0.01

100 – 99.98 = 0.02

(0.01/0.02) * 100 = 50%
(0.01/0.02) * 100 = 50%

	Physical Separation	**Biocidal Treatment**	**% Reduction**	**State**
	Zero	**Zero**		
Lower Bound	0	0	0.00	Zero
Upper Bound	0.899	0.899	80.82	Zero
	Zero	**Moderate**		
Lower Bound	0	0.9	0.00	Zero
Upper Bound	0.899	0.9998	89.88	Zero
	Zero	**High**		
Lower Bound	0	0.9999	0.00	Zero
Upper Bound	0.899	1	89.9	Zero

	Moderate	**Zero**		
Lower Bound	0.9	0	0.00	Zero
Upper Bound	0.9998	0.899	89.88	Zero
	Moderate	**Moderate**		
Lower Bound	0.9	0.9	81.00	Zero*
Upper Bound	0.9998	0.9998	99.96	Moderate*
	Moderate	**High**		
Lower Bound	0.9	0.9999	89.99	Moderate
Upper Bound	0.9998	1	99.98	Moderate
	High	**Zero**		
Lower Bound	0.9999	0	0.00	Zero
Upper Bound	1	0.899	89.90	Zero
	High	**Moderate**		
Lower Bound	0.9999	0.9	89.99	Moderate
Upper Bound	1	0.9998	99.98	Moderate
	High	**High**		
Lower Bound	0.9999	0.9999	99.98	Moderate**
Upper Bound	1	1	100.00	High**

Supplementary Table 4. Entropy reduction analysis for the initial risk estimates to Padilla Bay. The top three input parameters are listed with the entropy reductions values for each endpoint.

Endpoint	Input Parameter	Entropy Reduction
Water Quality		
Region 1	Currents	0.0163
	Marine Debris	0.0007
	Hull Fouling	0.0006
Region 2	Currents	0.0166
	Marine Debris	0.0006
	Hull Fouling	0.0005
Region 3	Currents	0.0106
	Marine Debris	0.0006
	Hull Fouling	0.0005
Region 4	Currents	0.0105
	Marine Debris	0.0006
	Hull Fouling	0.0005
Changes in Community Composition		
Region 1	Currents	0.0307
	Marine Debris	0.0013
	Hull Fouling	0.0012
Region 2	Currents	0.0287
	Marine Debris	0.0011
	Hull Fouling	0.0010
Region 3	Currents	0.0203
	Marine Debris	0.0013
	Hull Fouling	0.0011
Region 4	Currents	0.0204
	Marine Debris	0.0014
	Hull Fouling	0.0011
Dungeness Crab		
Region 1	Currents	0.0247
	Hull Fouling	0.0010
	Marine Debris	0.0010
Region 2	Currents	0.0229
	Marine Debris	0.0008
	Hull Fouling	0.0007
Region 3	Currents	0.0161
	Marine Debris	0.0010
	Hull Fouling	0.0009
Region 4	Currents	0.0161
	Marine Debris	0.0011
	Hull Fouling	0.0010
Juvenile Salmon		
Region 1	Currents	0.0135
	Marine Debris	0.0005
	Hull Fouling	0.0001
Region 2	Currents	0.0130

	Marine Debris	0.0005
	Hull Fouling	0.0004
Region 3	Currents	0.0075
	Marine Debris	0.0004
	Hull Fouling	0.0004
Region 4	Currents	0.0074
	Marine Debris	0.0005
	Hull Fouling	0.0004
Harbor Seal		
Region 1	Currents	0.0112
	Marine Debris	0.0004
	Hull Fouling	0.0004
Region 2	Currents	0.0101
	Marine Debris	0.0004
	Hull Fouling	0.0003
Region 3	Currents	0.0077
	Marine Debris	0.0005
	Hull Fouling	0.0005
Region 4	Currents	0.0078
	Marine Debris	0.0006
	Hull Fouling	0.0005
Birds		
Region 1	Currents	0.0132
	Marine Debris	0.0005
	Hull Fouling	0.0005
Region 2	Currents	0.0127
	Marine Debris	0.0005
	Hull Fouling	0.0004
Region 3	Currents	0.0087
	Marine Debris	0.0005
	Hull Fouling	0.0004
Region 4	Currents	0.0086
	Marine Debris	0.0005
	Hull Fouling	0.0004
Eelgrass		
Region 1	Currents	0.0191
	Marine Debris	0.0008
	Hull Fouling	0.0007
Region 2	Currents	0.0173
	Marine Debris	0.0007
	Hull Fouling	0.0006
Region 3	Currents	0.0126
	Marine Debris	0.0008
	Hull Fouling	0.0007
Region 4	Currents	0.0127
	Marine Debris	0.0009
	Hull Fouling	0.0007

Supplementary Table 5. Influence analysis: risk score comparison for the top three entropy input parameters when these parameters were set at 100% in the lowest state.

Endpoint	Input Parameter	Endpoint Risk Score	Endpoint risk score when the parameter is set at 100% of the lowest state	% Change in Overall Risk Scores
Water Quality				
Region 1	Currents	2.34	2.01	-14.10
	Marine Debris	2.34	2.32	-0.85
	Hull Fouling	2.34	2.27	-2.99
Region 2	Currents	2.27	1.83	-19.38
	Marine Debris	2.27	2.26	-0.44
	Hull Fouling	2.27	2.21	-2.64
Region 3	Currents	2.47	1.99	-19.43
	Marine Debris	2.47	2.45	-0.81
	Hull Fouling	2.47	2.40	-2.83
Region 4	Currents	2.49	2.01	-19.28
	Marine Debris	2.49	2.47	-0.80
	Hull Fouling	2.49	2.42	-2.81
Changes in Community Composition				
Region 1	Currents	3.63	3.24	-10.74
	Marine Debris	3.63	3.61	-0.55
	Hull Fouling	3.63	3.55	-2.20
Region 2	Currents	3.64	3.12	-14.29
	Marine Debris	3.64	3.62	-0.55
	Hull Fouling	3.64	3.56	-2.20
Region 3	Currents	3.92	3.38	-13.78
	Marine Debris	3.92	3.91	-0.26
	Hull Fouling	3.92	3.85	-1.79
Region 4	Currents	3.95	3.4	-13.92
	Marine Debris	3.95	3.93	-0.51
	Hull Fouling	3.95	3.87	-2.03
Dungeness Crab				
Region 1	Currents	3.04	2.7	-11.18
	Hull Fouling	3.04	2.97	-2.30
	Marine Debris	3.04	3.03	-0.33
Region 2	Currents	3.01	2.54	-15.61
	Marine Debris	3.01	3	-0.33
	Hull Fouling	3.01	2.94	-2.33
Region 3	Currents	3.35	2.88	-14.03
	Marine Debris	3.35	3.34	-0.30
	Hull Fouling	3.35	3.29	-1.79
Region 4	Currents	3.37	2.9	-13.95
	Marine Debris	3.37	3.36	-0.30

	Hull Fouling	3.37	3.31	-1.78
Juvenile Salmon				
Region 1	Currents	2.13	1.84	-13.62
	Marine Debris	2.13	2.12	-0.47
	Hull Fouling	2.13	2.07	-2.82
Region 2	Currents	2.1	1.72	-18.10
	Marine Debris	2.1	2.09	-0.48
	Hull Fouling	2.1	2.05	-2.38
Region 3	Currents	2.39	1.99	-16.74
	Marine Debris	2.39	2.38	-0.42
	Hull Fouling	2.39	2.34	-2.09
Region 4	Currents	2.41	2.01	-16.60
	Marine Debris	2.41	2.4	-0.41
	Hull Fouling	2.41	2.36	-2.07
Harbor Seal				
Region 1	Currents	0.94	0.77	-18.09
	Marine Debris	0.94	0.94	0.00
	Hull Fouling	0.94	0.91	-3.19
Region 2	Currents	0.92	0.7	-23.91
	Marine Debris	0.92	0.91	-1.09
	Hull Fouling	0.92	0.89	-3.26
Region 3	Currents	1.13	0.84	-25.66
	Marine Debris	1.13	1.12	-0.88
	Hull Fouling	1.13	1.09	-3.54
Region 4	Currents	1.15	0.85	-26.09
	Marine Debris	1.15	1.14	-0.87
	Hull Fouling	1.15	1.1	-4.35
Birds				
Region 1	Currents	2.28	1.99	-12.72
	Marine Debris	2.28	2.26	-0.88
	Hull Fouling	2.28	2.22	-2.63
Region 2	Currents	2.24	1.86	-16.96
	Marine Debris	2.24	2.23	-0.45
	Hull Fouling	2.24	2.18	-2.68
Region 3	Currents	2.39	1.97	-17.57
	Marine Debris	2.39	2.38	-0.42
	Hull Fouling	2.39	2.33	-2.51
Region 4	Currents	2.41	1.99	-17.43
	Marine Debris	2.41	2.4	-0.41
	Hull Fouling	2.41	2.35	-2.49
Eelgrass				
Region 1	Currents	3.17	2.76	-12.93
	Marine Debris	3.17	3.15	-0.63
	Hull Fouling	3.17	3.08	-2.84

Region 2	Currents	3.15	2.61	-17.14
	Marine Debris	3.15	3.13	-0.63
	Hull Fouling	3.15	3.07	-2.54
Region 3	Currents	3.5	2.89	-17.43
	Marine Debris	3.5	3.48	-0.57
	Hull Fouling	3.5	3.41	-2.57
Region 4	Currents	3.53	2.92	-17.28
	Marine Debris	3.53	3.51	-0.57
	Hull Fouling	3.53	3.44	-2.55