Integrated Environmental Assessment and Management — Volume 11, Number 4—pp. 640–652

Evaluating Nonindigenous Species Management in a Bayesian Networks Derived Relative Risk Framework for Padilla Bay, WA, USA

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(Submitted 4 December 2014; Returned for Revision 20 January 2015; Accepted 16 March 2015)

ABSTRACT

Many coastal regions are encountering issues with the spread of nonindigenous species (NIS). In this study, we conducted a regional risk assessment using a Bayesian network relative risk model (BN-RRM) to analyze multiple vectors of NIS introductions to Padilla Bay, Washington, a National Estuarine Research Reserve. We had 3 objectives in this study. The 1st objective was to determine whether the BN-RRM could be used to calculate risk from NIS introductions for Padilla Bay. Our 2nd objective was to determine which regions and endpoints were at greatest risk from NIS introductions. Our 3rd objective was to incorporate a management option into the model and predict endpoint risk if it were to be implemented. Eradication 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. We incorporated the ballast water treatment management scenario into the model, observed the risk to the endpoints, and compared this risk with the initial risk estimates. The model results indicated that the southern portion of the bay was at greatest risk because of NIS. Changes in community composition, Dungeness crab, and eelgrass were the endpoints most at risk from NIS introductions. The currents node, which controls the exposure of NIS to the bay from the surrounding marine environment, was the parameter that had the greatest influence on risk. The ballast water management scenario displayed an approximate 1% reduction in risk in this Padilla Bay case study. The models we developed provide an adaptable template for decision makers interested in managing NIS in other coastal regions and large bodies of water. *Integr Environ Assess Manag* 2015;11:640–652. ©2015 SETAC

Keywords: Relative risk model   Bayesian networks   Nonindigenous species   Dungeness crab   Invasive species management

INTRODUCTION

Humans introduce nonindigenous species (NIS) to coastal systems from a number of activities and pathways. Nonindigenous species affect communities by causing major alterations (positive or negative) in community structure. The impacts may be losses, such as population declines via competition or predation, or benefits, such as providing additional food sources or shelter to native species (Pauley et al. 1986; Cohen et al. 1995). Of the thousands of species introduced to a new community, only a few will substantially impact a habitat (Andersen et al. 2004). In this study, we conducted an ecological risk assessment and analyzed the risk from various vectors of NIS introductions to coastal communities.

Risk assessment

Over the past 2 decades, a movement has arisen in the field of ecological risk assessment to understand environmental issues at larger spatial scales. In the late 1990s, Landis and Wiegers (1997) introduced the relative risk model (RRM) that addresses issues at a landscape scale, analyzing multiple sources of stressors, habitats, and the resulting impacts on the endpoints. The RRM calculates risk, using ranks, to endpoints based on causal links of stressors entering a habitat (exposure) and an interaction between the stressor and endpoint resulting in an effect. The causal pathways allow risk assessors to distinguish the habitats with greatest exposure and endpoints most at risk (Landis and Wiegers 1997, 2005).

In the early to mid-2000s, the RRM approach was used to create conceptual models to describe pathways of NIS introductions (Landis 2003; Colnar and Landis 2007; Landis et al. 2010; Seebach et al. 2010). Landis (2003) analyzed general vectors of introduction for many taxa of NIS. Colnar and Landis (2007) focused on 1 species, the European Green Crab (*Carcinus maenas*), and the hierarchical patch dynamic paradigm (Wu and David 2002 and references cited therein) to integrate various spatial aspects. Deines et al. (2005) modeled patch-dynamic interactions with habitat disturbance from a hypothetical contaminant. Recently, the RRM was adapted to use Bayesian networks (BNs) to estimate risk, such as impacts to forested habitats from wildfire, grazing, and forest management activities (Ayre and Landis 2012), prespawn mortality of Coho salmon in the Pacific Northwest (Hines and Landis 2014), and whirling disease in cutthroat trout (Ayre et al. 2014).

Bayesian networks are graphical models used to describe cause-and-effect relationships, and in this way they are very similar to the conceptual models that typically are used in risk

All Supplemental Data may be found in the online version of this article.
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Published online 3 April 2015 in Wiley Online Library (wileyonlinelibrary.com).
DOI: 10.1002/ieam.1643

assessment. Parent nodes do not have inputs. Child nodes receive inputs from 2 or more parent nodes. Conditional probability tables (CPTs) are used to describe the interactions between the parent nodes that result in the child node. The CPTs describe the probability of all potential outputs given the different combinations of the input variables. Bayesian networks are acyclic, meaning that explicit feedback loops are not permitted. A more technical description of Bayesian networks and their use in environmental management can be found in Woodberry et al. (2004), Pollino et al. (2006), Marcot et al. (2006), McCann et al. (2006), Nyberg et al. (2006), and Carriger and Barron (2011).

As reported in Ayre and Landis (2012), we have translated the form of the relative risk model into a Bayesian network to calculate relative risk and to incorporate management options. The same process also has been applied to examine the risk of stormwater runoff to Coho salmon (Hines and Landis 2014) and risk of whirling disease to isolated trout populations (Ayre et al. 2014). In each instance the source-stressor-habitat-effect-impact causal pathway of the relative risk model is translated into the form of a Bayesian network. This transformation is described in detail in the "Derivation of the BN-RRM for invasive species" section of the methods. The resulting Bayesian network relative risk model (BN-RRM) has proved useful in examining the effects of multiple stressors of various types to multiple endpoints.

Several of the characteristics of BNs lend themselves to the risk assessment of nonindigenous species. Bayesian networks innately incorporate the deterministic and stochastic aspects of complex systems, deal well with uncertainty, and provide probabilistic predictions with measures of the importance of the variables (sensitivity analysis). The characteristics of various management options can be incorporated into the BN-RRM and the changes in risk estimated (Nyberg et al. 2006; Ayre and Landis 2012; Hines and Landis 2014). These characteristics are important in marine systems, where NIS data are sparse, the ecological systems are complex, and a variety of potential management strategies exist.

We conducted a landscape-scale risk assessment to determine the effects of NIS colonization on coastal habitats and the use of a management approach to reduce propagule concentrations. Bayesian networks were constructed to determine risk of NIS introduction and establishment in the Padilla Bay National Estuarine Reserve, Padilla Bay, Washington, USA. Although the model formation and implementation are described specifically, using Padilla Bay as a case study, this approach can be adapted for many bodies of water, such as the Great Lakes, large river systems, coastal areas, and estuaries.

Nonindigenous species

For thousands of years, humans have accelerated the dispersal of NIS through shipping activities, particularly ballast water and hull fouling (Sylvester et al. 2011). The improper disposal of organisms in the packaging of live bait and seafood also can lead to NIS introductions (Pimentel et al. 2005; Colnar and Landis 2007). Furthermore, dispersion of NIS has resulted from intentional actions such as introducing species via aquaculture practices (e.g., transplanting nonnative shellfish) or from efforts to stabilize shorelines, such as with the cordgrass *Spartina* spp. (Thompson 1991; Wallentinus and Nyberg 2007).

Aquatic NIS influence the environment they colonize by changing habitats, species biodiversity, and ecological function. They compete with native species for resources, prey on native species, and some NIS transfer diseases when they are consumed by native species (Landis 2003; Pimentel et al. 2005; Ruiz and Smith 2005; Colnar and Landis 2007). Additionally, some NIS induce physical or chemical changes to the habitat (Wallentinus and Nyberg 2007). Millions of US dollars are spent every year on damages caused by NIS and on eradication efforts (Pimentel et al. 2005).

A diverse community may prevent NIS from establishing and spreading (Andersen et al. 2004). Consequently, settlement and establishment of NIS become easier if a system is disturbed (Mack and D'Antonio 1998; Didham et al. 2005). Then a NIS can become abundant and dominate a community, decreasing populations of other species (Wallentinus and Nyberg 2007).

Studies have attempted to estimate the effects of NIS from many vectors of introduction (ballast water, full fouling, and marine debris; Coutts and Taylor 2004; Lewis et al. 2005; Ruiz and Smith 2005). Relatively few of the studies analyze the effects from NIS introductions from a landscape scale perspective (see Landis 2003; Colnar and Landis 2007). Furthermore, a common theme and hindrance 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). Although some data are available, much is not statistically robust. For instance, detection limits require water volume samples of 30 to 60 m^3 to portray the diversity of organisms and their concentrations in ballast water (Albert et al. 2010; USEPA SAB 2011). Likewise, researchers examining hull fouling state that the number of vessels analyzed was too small and not representative of all vessels entering port (Ruiz and Smith 2005; Davidson et al. 2006). In this study, we conducted an ecological risk assessment and estimated risk from NIS introductions at a landscape scale.

Study objectives

We had 3 objectives in this study. The 1st objective was to determine whether the BN-RRM could be used to calculate risk from NIS introductions for Padilla Bay. Our 2nd objective was to determine which regions and endpoints were at greatest risk from NIS introductions. Our 3rd objective was to incorporate a management option into the model and predict endpoint risk if it were to be implemented.

Before addressing these objectives, we must first explain the methodology of the modeling process. We start with a description of the study site and risk regions. Next, we provide a detailed account of the BN-RRM process, including the initial construction of the model framework as well as the model parameterization. We discuss 2 risk scenarios, the initial risk estimates for each endpoint and risk with a management scenario (ballast water treatments). The results indicated that the greatest risk occurs to the southern portion of the bay. The sensitivity analysis showed that the node currents, a vector of introduction and source of NIS exposure, had the greatest influence on risk compared with the remaining vectors of introduction (e.g., ballast water, hull fouling, and marine debris).

METHODS

Padilla Bay study site

Padilla Bay is an estuarine system in Skagit County, Washington, USA, known for its extensive eelgrass beds.

Tidal fluxes transport water 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 1980, Padilla Bay was designated as the 8th National Estuarine Research Reserve (PBNERR 2008). The Padilla Bay National Estuarine Research Reserve (PBNERR) is characterized by a flat intertidal zone, much of which drains with ebbing tides, and deeper channels intersecting the bay. The PBNERR has unique eelgrass beds, covering approximately 3200 ha (Bulthuis 1991). Eelgrass beds provide habitat, food, and nursery grounds for many species, such as Dungeness crab and other invertebrates, and vertebrates, including juvenile salmon, local and migratory birds, and marine mammals (PBNERR 2008).

Many nonnative organisms currently reside in the PBNERR, and most of these species 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), as was the Japanese littleneck clam (*Venerupis philippinarum;* Riggs 2011). Additional nonnative species include eelgrass (*Zostera japonica)*, softshell 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 likely was introduced from ballast water (PBNERR 2008; Riggs 2011). Cordgrass (*Spartina* spp.) is still found in the bay; however, eradication efforts have reduced the population to less than one-tenth of an acre (PBNERR 2008).

Determination of risk regions

We separated the PBNERR into 4 risk regions, based on the watersheds, channels in the bay, and the agriculture, industry, forest, and urban land use as mapped in ArcGIS (Esri, Redlands, CA, USA) (Figure 1). Data were obtained from the National Estuarine Research Reserve System Centralized Data Management Office (CDMO 2013) and Suzanne Shull

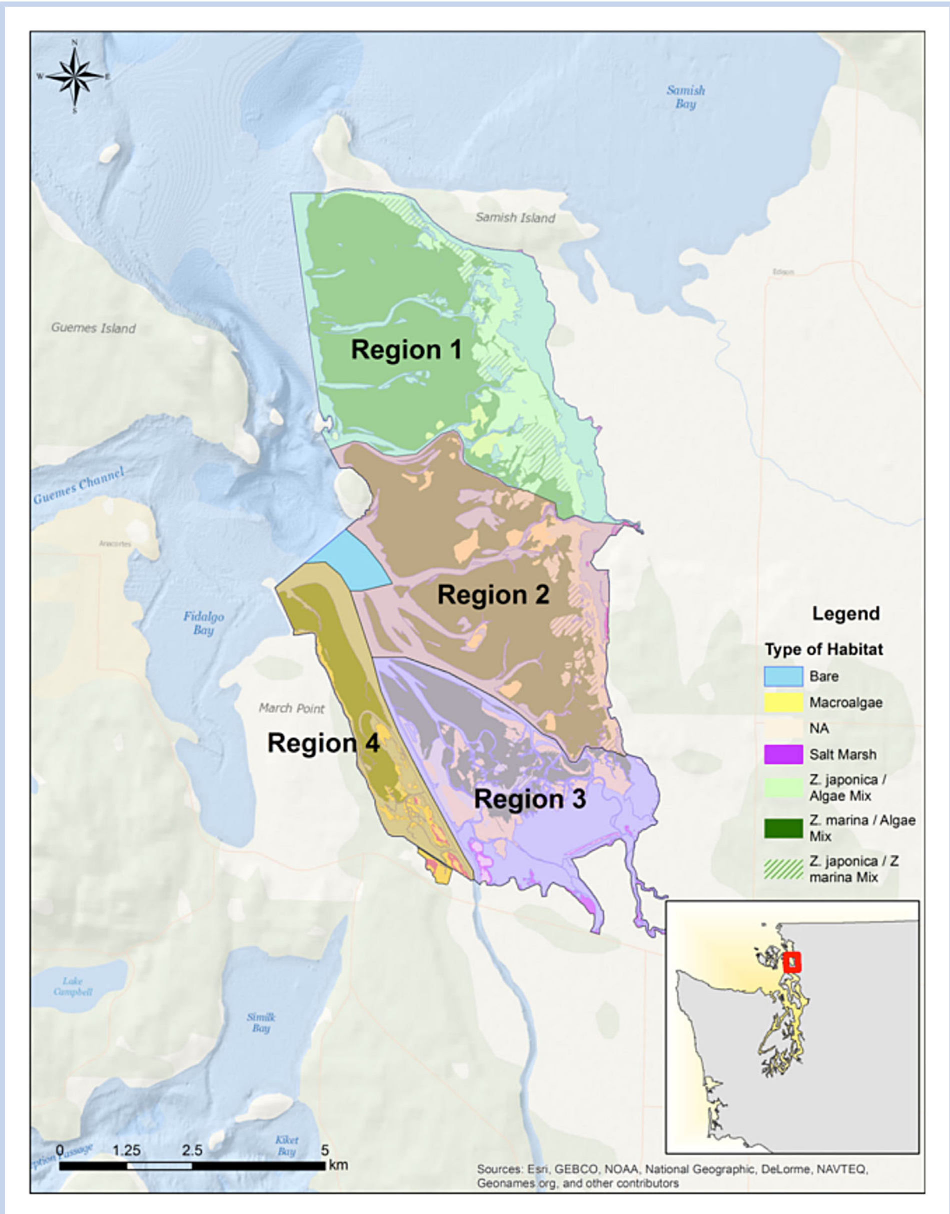

Figure 1. Map of Padilla Bay National Estuarine Research Reserve (PBNERR) with the risk regions identified. Risk regions were determined based on watersheds and adjacent land use, and were consistent with previous studies by Bulthuis (1991).

from the PBNERR. The specific boundaries for the 4 risk regions were consistent with earlier work by Bulthuis (1991). The total area of the study site is 61.35–km^2.

The land and water use adjacent to the bay comprises agricultural, urban, industrial, shipping, and recreational activities (e.g., boating and crabbing). Pollutants from runoff from these activities may disturb aquatic habitats and indirectly facilitate NIS settlement. The Padilla Bay watershed drains approximately 23 000 acres (9308 ha) of land mainly via 3 sloughs, some of which are on the Impaired Water List (PBNERR 2008).

Direct vectors of NIS introductions and exposure of NIS occur from hull fouling and ballast water discharges associated with vessels entering March Point and Anacortes ports. Currents transport NIS, depending on the tides, either east into Padilla Bay, south into the Swinomish Channel, or west into the Guemes Channel (Bulthuis and Conrad 1995a, 1995b). Additional exposure of NIS arose from the secondary transport of NIS from other ports or patches of already settled NIS.

Derivation of the BN-RRM for invasive species

The construction of the BN-RRM started with the creation of a conceptual model used to map the cause-and-effect pathways from the sources of stressors to the endpoints. The conceptual model created the basic framework of an influence diagram for the BN. Next, the conceptual model was formatted into a BN structure, and the rankings for the nodes and the relationships described by the CPTs were derived. Once the model was complete, we calculated the endpoint risk and estimated parameter sensitivity by conducting an entropy reduction analysis. In addition to the initial risk calculations, we modeled risk with a management scenario and compared these 2 outcomes. Total risk distributions (for each endpoint) for both scenarios were compared via additive risk curves. The details for each step are presented next.

Conceptual model. The conceptual model was based on that described by Landis (2003) as implemented by Colnar and Landis (2007) (Figure 2). The first step in creating the conceptual model was determining the endpoints. Discussions with managers of the PBNERR revealed the species and endpoints of interest. These included juvenile salmon, harbor seal, Dungeness crab, eelgrass (*Zostera marina*), and a variety of birds. Some birds were permanent residents, such as the great blue heron. Other birds included migratory species that only winter in Padilla Bay, such as the black brant. Additional endpoints considered were water quality and changes in community composition.

Next we identified the sources for the stressors affecting the endpoints. Our model includes the sources' shipping activities (ballast water discharge and hull fouling), NIS attached to marine debris, and currents dispersing NIS from local patches. Through data and findings from literature searches, we established causal linkages from the stressors to habitats (exposure) and the resulting effects to the endpoints. The exposure and effect links were essential in determining whether the stressor arrived at the habitat and whether the endpoint used the habitat.

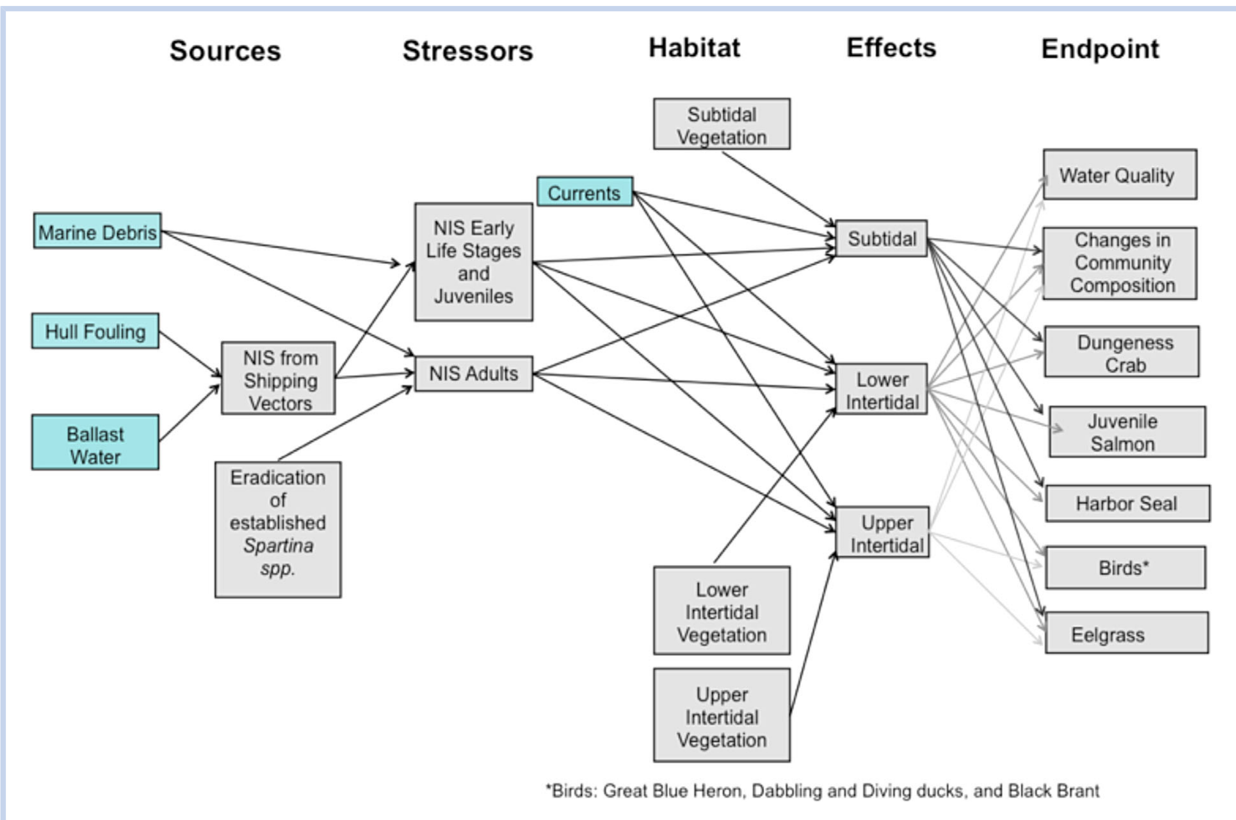

Figure 2. Nonindigenous species (NIS) conceptual model for the Padilla Bay National Estuarine Research Reserve (PBNERR). The teal boxes indicate the vectors of NIS introduction.

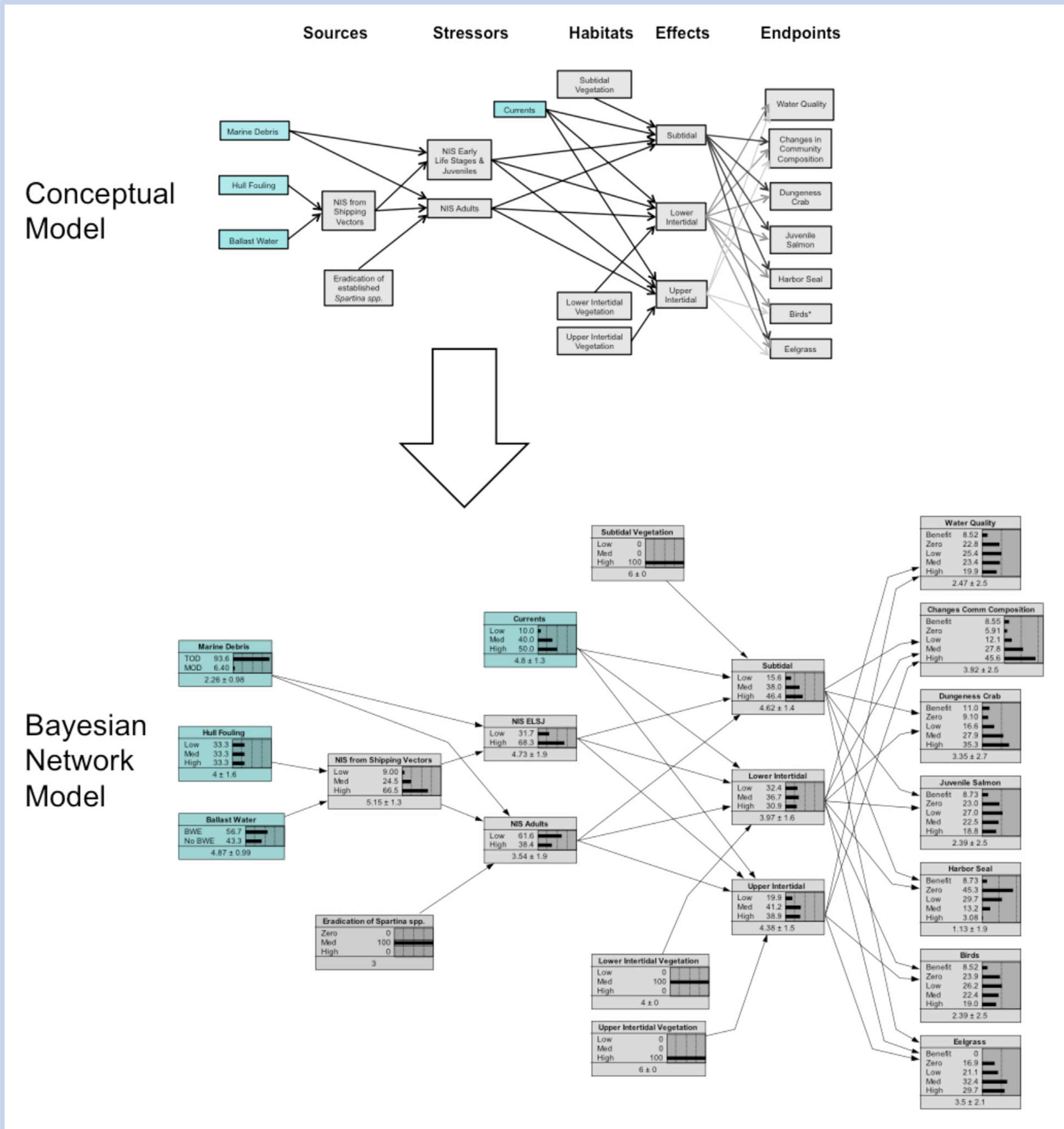

Figure 3. Conceptual model transformation into the BN. The conceptual model provided the structural framework for the BN. The BN quantitatively define risk to each of the endpoint nodes in the model. The teal nodes represent the vectors of nonindigenous species (NIS) introduction. The vertical dashed lines in the nodes represent quartiles. The values at the bottom of each node represent the risk score, which is the mean of each distribution.

The causal pathway for the NIS model began with the vectors of introduction releasing organisms of various life stages (early life stages and juveniles or adult organisms) to the surrounding waters. Currents transport the organisms to various habitats in each region. Once the NIS arrives in the habitat, 3 additional steps are necessary for a species to become an NIS (Andersen et al. 2004). The species has to establish itself by reproducing and expanding its population. If this does not happen, local extinction occurs. Next, the population must spread from its point of entry, finding available space in the surrounding habitat. Finally, the species has to affect the community. 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 3rd stage and co-exist in a habitat with other organisms (Andersen et al. 2004), causing no major alteration to the community.

BN structure. The conceptual model provided the framework for the BNs (Figure 3). The BN structure in the BN-RRM contains various tiers (Ayre and Landis 2012). The 1st tier represents the parent or input nodes; these nodes have no links (arrows) entering them. We incorporated prior knowledge and data into these parent nodes. The 2nd tier consists of child nodes. The child nodes are distinguished with incoming and outgoing arrows (McCann et al. 2006), indicating a probabilistic interaction with the parent nodes. The last tier includes the endpoint nodes, which have only incoming links. The endpoint nodes present the expected risk from the stressor, habitat, and endpoint interaction.

Each node in the BN represents a box from the conceptual model (Figure 3). All nodes in the model were classified as nature nodes, representing either a distribution across many states or a fixed state. We evaluated all nodes for uncertainty, and that is represented by the distributions of the various states. Fixed nodes did not have uncertainty associated with them because only 1 state was possible for that parameter. The BN-RRM is transparent about epistemic uncertainty.

We determined the number of states for each node based on the availability and quality of data, and scientific literature supporting each variable. Nodes generally had 3 states, with the high state corresponding to the largest amount of the stressor, exposure, or effect occurring in the system. In the management nodes, the high state represented the greatest reduction in the stressor. We used binomial states when only 2 options for a node existed, because the data indicated that only 2 states are possible or a lack of data or knowledge precluded distinguishing among 3 states. The endpoint nodes in this model contained 5 states with an accompanying score. These states and scores are benefits (−2), zero (0), low (2), medium (4), and high (6), following the original scoring style of the RRM.

The full version of the BN software Netica (Norsys Software Corp., Vancouver, BC, Canada) was used to calculate and evaluate the BN-RRM. A limited edition of this software that can read models and save changes to small models may be downloaded for free. The models described here can be read, modified, and saved by either version. The models written in Netica are available as downloads, and instructions are found in the section Notes for downloading and viewing the BN models.

The model results (described in the endpoint nodes) can be described in 2 ways, by risk scores and risk distributions. Risk distributions are represented by bars depicting the likelihood of risk associated with each state of risk. The risk score presented in the Netica framework is the mean value of the distributions of each risk state accompanied by the standard deviation.

Model derivation. We derived the values used in the BN with a combination of quantitative data, federal regulations, and knowledge and data obtained from peer-reviewed scientific literature and technical reports (see references in Supplemental Data Table ST-1). This process in the construction of BNs for ecological management was coined parameterization, as exemplified in Marcot et al. (2006). Model parameterization had 2 steps. First, we defined the states for each node. For example, the Ballast Water node was represented by 2 states: vessels that had undergone a ballast water exchange (BWE) at sea and vessels that did not exchange ballast water (no BWE) (Table 1). Second, the CPTs were completed with available data or prior knowledge about parameter interactions. The CPTs are a way to analyze the probabilistic distributions for every combination of the parent nodes entering the child node. We used evidence and data from peer-reviewed scientific literature and technical reports to determine the probabilistic exposure–response interactions for each combination of parent nodes in the CPTs (Table 2). The tables that summarize this process are available in Supplemental Data Table ST-1, and CPTs can be viewed in the tables of the models (models SM-1–4).

Vectors of introduction. The vectors of introduction we analyzed were ballast water, hull fouling, marine debris, and the secondary transport of NIS from currents. Data sources for

Table 1. Model parameterization for 2 of the inputs for the BN[a]

Model variable and definition	Variable state	Justification	References
Ballast water			
Midocean ballast water exchange (BWE) from empty-refill or flow-through methods	BWE ≤90% reduction in propagules	BWE can result in a 90% reduction of zooplankton. To pass Phase I Standards, this means vessels can only have 100 organisms/m^3 of water. Only ∼17% of vessels will pass the Phase I standards with a BWE. Ballast water exchanges reduce coastal organisms in ballast tanks; however, many organisms are still discharged into the receiving port.	Minton et al. 2005
No ballast water exchange	No BWE	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 mo	Ships have recently been dry-docked and have undergone hull maintenance (defouling of the hulls and application anti-fouling paint). After 12–14 mo, hulls remained relatively free of fouling.	Coutts and Taylor 2004; Sylvester et al. 2011
	Medium 14–36 mo	Fouling of the hulls observed after ∼14 mo since last dry dock.	
	High >36 mo	Vessels in the water for >36 mo displayed more fouling. Anti-fouling paint wears with time, after 3+ y vessels are ready for dry-docking and re-application of anti-fouling paint.	

[a]For a complete explanation of model input distributions and justification, see Supplemental Data Table ST-1.

Table 2. Conditional probability table (CPT) for the NIS from shipping vectors node[a]

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

[a]This node analyzed the interaction between the Ballast Water and Hull Fouling parent nodes. Both vectors are equally likely to introduce NIS to coastal regions. We represented this in the probability distributions in the CPT: the parent combination of medium hull fouling and no-ballast water exchange (No BWE) had the same probability as the high state of hull fouling and a BWE for the ballast water node. The BWE in this risk assessment was equivalent to medium effect.

these vectors included the National Ballast Information Clearinghouse (NBIC) for the ballast water discharge data and Ocean Conservancy International Beach Clean-up data for the marine debris data. No data were available for the hull-fouling vector; thus, an equal distribution of 33.3% was given to each state. The currents data were extracted from Bulthuis and Conrad (1995a, 1995b).

The NBIC data consisted of ballast water discharge forms submitted 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), or whether an alternative treatment was used. In analyzing the records, we determined the frequencies of vessels having undergone a BWE versus no BWE for ships entering the Ports of Anacortes and March Point from January 2011 through December 2013. We then summed the total vessel arrivals for the 3 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 or vessels that did not discharge ballast were excluded. Ships with incomplete ballast water exchanges were counted as no BWE. Discharge after a midocean ballast water exchange reduces the concentration of coastal propagules and likely the number of NIS (Minton et al. 2005). Most vessels that did not exchange ballast water were coastal voyages and were traveling within the common water agreement, Washington Revised Code § 77.120.030. These vessels could be vectors in the secondary transport of NIS (Lawrence and Cordell 2010).

The Ocean Conservancy collected marine debris data during their annual International Beach Clean-up. Only debris data collected in the state of Washington were used. Debris was classified as marine origin debris and terrestrial origin debris (TOD; JTMD 2012). The marine origin debris consisted of buoys, floats, and other items submerged in coastal waters before becoming free-moving debris and thus had a greater likelihood of transporting NIS. The TOD included debris originating on land before being washed into the ocean. This debris likely spent less time in coastal waters and had a lower probability of transporting NIS. The data collected only analyzed the type of debris; no analysis was conducted on the taxonomy of organisms attached to the debris.

The last vector we analyzed consisted of currents transporting established NIS from patches adjacent to the PBNERR. Note that the currents were also our link of exposure. We did not separate the currents node into 2 separate nodes because the data sources were the same and the nodes would not be independent of each other. The currents were determined from the predominate flow of water to each region. The Ports of Anacortes and March Point were closest to Padilla Bay and a source of NIS introductions from ballast water discharges and hull fouling. However, many vessels were anchored in waters surrounding the PBNERR while awaiting entry into these ports. Thus, currents from the north and west could also transport NIS to the bay from hull fouling vectors. Furthermore, currents from the Swinomish Channel (south) transport propagules of *Spartina* spp. yearly to the southern portion of Padilla Bay.

To determine the predominate flow of water into the bay; we used drift stick studies, conducted by Bulthuis and Conrad (1995a, 1995b), to understand water movement from the south and west into Padilla Bay. Current exposure pathways from the north are not well understood, so uncertainty was assigned to the input distributions for the currents node, illustrated by a more equal distribution for regions 1 and 2 than for regions 3 and 4. However, all of the regions were assigned uncertainty with the currents vector because of seasonal changes and lunar cycles.

Management scenario

A ballast water treatment management scenario was incorporated into the BN-RRM (Supplemental Data Table ST-1, Figures SF-5–8, and Models SM-5–8). We analyzed 2 options for reduction of propagules in ballast water: physical separation (filtration) and physical and chemical treatments (e.g., electrochlorination, chlorine dioxide, deoxygenation, and cavitation, ultraviolet light [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). We set the ballast water treatments to high reduction, with the exception of the physical separation node, in which a medium reduction state was used because high reduction was not possible due to limitations in filter sizes (Albert et al. 2010). Thus, the management scenario represented the highest level of stressor reduction attainable from the mitigation treatments and provided results on the expected reduction of risk to each endpoint.

Model derivation: Management scenario. We based the rankings for the management nodes on the ability of the treatments to reduce concentrations of organisms in ballast water (Supplemental Data Tables ST-1 and ST-2). A high state indicated a greater reduction of propagule pressure than a state of zero. The zero state represents reductions of 0% to 89.9%. Although the upper bound may seem high, BWE can reduce propagules by 90% (Minton et al. 2005). Therefore, successful ballast water treatments need reductions of 90% or more. To obtain a moderate ranking, vessels need an efficacy of 90% to 99.98%, and high rankings require reduction rates of 99.99% to 100% (Supplemental Data Table ST-2). Calculations for rankings were determined from the United States Coast Guard Phase I Standards (number of allowable organism in discharged ballast water). The Phase I Standards are described in Albert et al. (2010), Lee et al. (2010), and USEPA SAB (2011).

Risk calculations

Once we completed model derivation for the initial risk estimates scenario and the management scenario, we ran the models for each region. The interaction between NIS and native species was associated with risk states (zero, low, medium, and high states) and a benefits state. The risk, the probability of an undesirable effect to an endpoint determined by society to be important (Hines and Landis 2014), included the introduction of diseases to native species, population declines caused by competition and predation by the NIS, and changes to the habitat. Benefits included additional food and shelter for the native species. The calculation of risk had 2 components, the risk distributions and risk scores. Risk distributions were represented by the percent probability of risk associated with each state given the prior knowledge (evidence entered in the input nodes). The risk score, the number located at the bottom of each node, was the mean value of the distributions for that node. After running the models, we completed a sensitivity analysis for each endpoint.

Sensitivity and uncertainty: Entropy reduction

We conducted entropy reduction analyses to determine which input variables had the most influence on the endpoints. Entropy analysis is analogous to correlation analysis when discrete states are used (Marcot 2012). Sensitivity analyses were conducted using the Netica modeling software.

Sensitivity and uncertainty: Influence analysis

Influence analysis is also a tool for estimating sensitivity and uncertainty. (Marcot 2012). In an influence analysis, we are essentially determining the maximum and minimum risk ranges. To complete the influence analysis, we set the distribution of the node to its low state (e.g., currents set to the low state or marine debris set to the TOD state). We then record the risk score, compare it with the initial risk estimate, and calculate the percent change in risk. This analysis allowed us to predict the percent reduction in risk that would be obtained if management targeted these variables.

Interactive tools and uses of model

The model also can act as an interactive tool for managers and decision makers. For instance, we can set an endpoint value to a specific state (e.g., low) and observe changes throughout the model, creating a back-calculation of risk to the input nodes. This process allows an estimation of model conditions that result in a desired outcome.

Total risk calculations

We calculated the values of the risk distributions of each endpoint of all 4 regions by using a Monte Carlo approach. Recall that each endpoint rank was a value from −2 to 6. The endpoint nodes provide the frequencies of each of these values. With 4 risk regions, the range for values for each endpoint over the entire study site ranged from −8 to 24. The rankings of risk in the output were set at −8 to −2 for benefits, 0 to 8 for low, 10 to 16 for medium, and 10 to 14 for high. The Monte Carlo tool (Crystal Ball Oracle version 11.1.2.3.000) sampled (10 000 iterations, Latin Hypercube) each endpoint node. The values were then added to derive the distribution of risk for each endpoint over all risk regions. This process was followed for both the initial risk estimates and then the risk after employing Ballast Water Treatment.

RESULTS

Risk by regions: Initial risk estimate

Each risk region exhibited a specific distribution of risk to the endpoints. Region 4 (March Point) had the highest risk, with probability distributions largely in the medium and high states. Region 3 (South) had similar distribution patterns to region 4. However, the probabilities in region 3 were shifted slightly to the lower states because of moderate eradication of the NIS, *Spartina* spp. Regions 1 and 2 had similar distributions and risk scores. The distributions of risk were shifted to the lower states (zero and low states) in regions 1 and 2 compared with the results from regions 3 and 4 (Supplemental Data Figures SF-1–8 and Models SM-1–8).

Risk by endpoints

Initial risk estimate. The change in community composition endpoint was skewed to the medium- and high-risk states. Combined, these states represented 67% to 74% probability of impacts occurring (Figure 4A, Supplemental Data Figures SF-1–4). The eelgrass and Dungeness crab endpoints also had distributions skewed to the medium and high states, corresponding to 55% to 64% of the total probability of risk (Figure 4B, Supplemental Data Figures SF-1–4). Water quality, birds, and juvenile salmon endpoints had similar risk patterns, with a fairly equal distribution between the zero, low, and medium states, each with a 20–28% likelihood of risk (Figure 4C, Figures SF-1–4). The harbor seal endpoint had the lowest risk in every region, with most of the risk (75%–80%) distributed in the zero and low states (Figure 4D; Supplemental Data Figures SF-1–4). The distribution for the benefits state was similar across endpoints (∼8%–11%), with the exception of the eelgrass endpoint, which had no benefits.

Risk after management scenario. The implementation of the ballast water treatment management scenario produced little change in the risk distributions and risk scores. A slight shift (∼1%) was seen in risk from the high states to the zero and low states (Figure 5, Supplemental Data Figures SF-5–8).

Sensitivity and uncertainty: Entropy reduction analysis

The sensitivity results indicated that the currents node had the greatest influence on endpoint risk (Supplemental Data, Figure SF-9, Table ST-3). The currents node greatly outweighed all of the other nodes in its ability to influence risk to each endpoint. This feature was observed for all regions and endpoints. In contrast, the ballast water node had very little effect on endpoint sensitivity (Figure SF-9).

Sensitivity and uncertainty: Influence analysis

When we completed the influence analysis, setting the nodes to their lowest states, the currents node resulted in the largest reduction in endpoint risk (10%–25%). The hull fouling vector resulted in an estimated 2%–5% reduction of endpoint risk, followed by the marine debris node, with a 1% reduction of endpoint risk (Supplemental Data, Table ST-4). The marine debris node was already skewed to the TOD state (equivalent to a low state), which accounted for the small percent change in risk reduction to the endpoints.

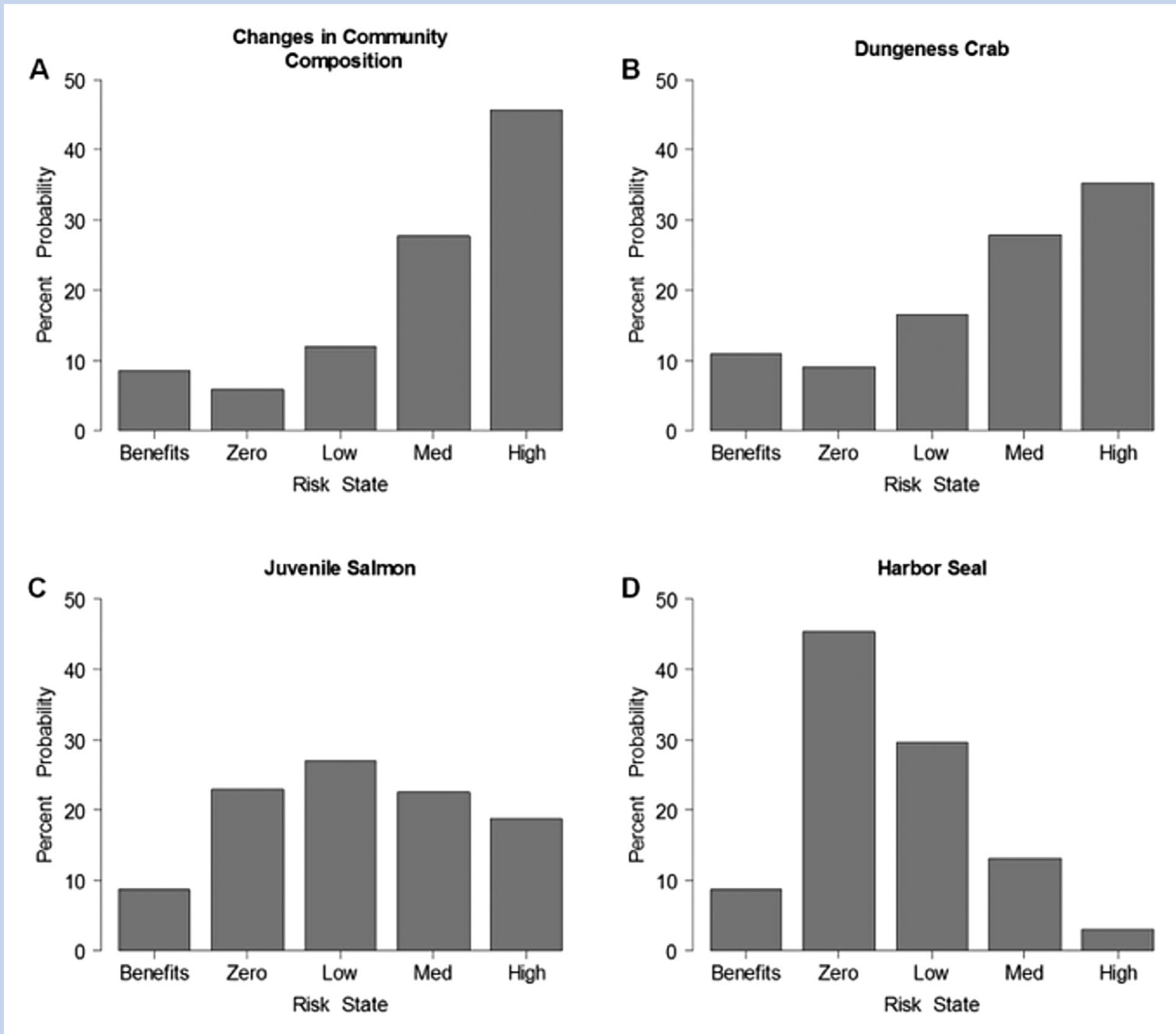

Figure 4. Graphical representations of endpoint distributions displaying the initial risk percent probabilities for 4 endpoints: (A) Changes in community composition. (B) Dungeness crab. (C) Juvenile salmon. (D) Harbor seal. These distributions are specifically from region 3. The endpoints with the highest risk are changes in community composition and Dungeness crab (skewed right); juvenile salmon risk was skewed to the zero, low, and medium states; and the harbor seal is at lowest risk (skewed left).

Interactive tools and uses of model

When we conducted back-calculation scenarios for a number of endpoints, the parameters that changed the most were the habitats, currents, and the specific life stages of NIS (stressors) nodes. 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 suggests more influence with the currents node, the exposure of the NIS, and secondary movement of NIS. These results agree with the findings from the sensitivity analysis.

Total risk for each endpoint

The risk calculations for each endpoint over the entire study area are presented as distributions in Figure 6. Dungeness crab and community composition are the endpoints with the most values in the high category. Compared with other endpoints, the harbor seal endpoint demonstrated the largest scores in the benefits range, although these frequencies were low compared with the low- and medium-risk values.

When risk following the implementation of ballast water treatment was calculated, the scores shifted only slightly to the lower-risk direction for each endpoint. The order of endpoints at risk did not change.

DISCUSSION

We demonstrated that the BN-RRM approach was successful in calculating risk from NIS introductions and impacts to coastal regions and endpoints. Using sensitivity analysis, we determined that the currents node had the greatest influence on the endpoints. We were also able to incorporate a management scenario and compare risk from this scenario with the initial risk estimates. In this instance, the use of ballast water treatment resulted in little effect to the overall risk calculation.

Patterns of risk

Initial risk estimates. Risk from NIS introductions was greatest in the southern portion of the PBNERR. These regions had the lowest percent cover of vegetation and greatest exposure to currents (Bulthuis and Conrad 1995a, 1995b). The changes in

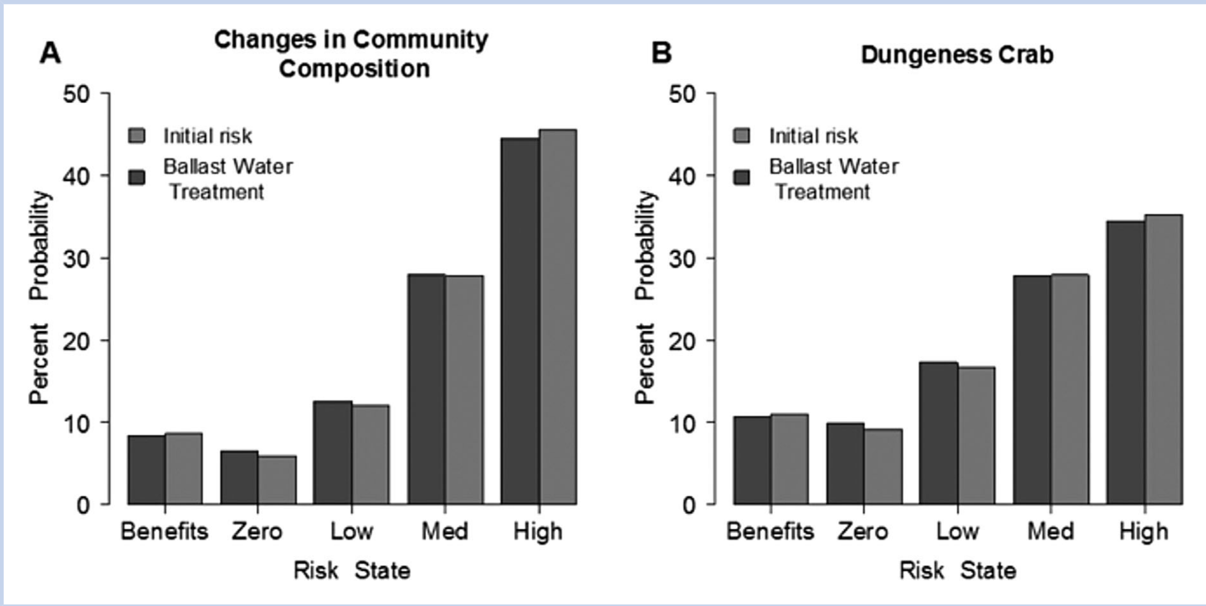

Figure 5. Risk comparison for the initial risk estimates and the ballast water treatment management scenario for region 3. The changes in community composition and Dungeness crab endpoints had the greatest change in risk distributions, with a shift in risk of only approximately 1%.

community composition, eelgrass, and Dungeness crab endpoints were most at risk from NIS introductions and effects. Part of the greater risk to these endpoints is because they remain in the habitat year round (eelgrass and juvenile Dungeness crabs) instead of seasonally (PBNERR 2008).

The currents node had the greatest influence on endpoint risk. Currents are the exposure route of NIS to the bay, as well as a vector transporting NIS from patches in adjacent coastal areas to Padilla Bay. These results, indicating that the currents were most influential on endpoint risk, demonstrate the importance of hierarchical patch dynamic paradigm and spatial scales. For instance, we must consider the local movement of water from ports with NIS introductions from shipping activities. At regional scales, currents transport NIS from established patches in the Salish Sea or the west coast of the United States, such as the movement of the European green crab (Colnar and Landis 2007). Currents also can transport NIS from a much larger scale with the movement of marine debris worldwide (JTMD 2012). The entropy results convey the importance of currents as a link of exposure and the secondary transport of NIS from existing patches.

Change in community structure and Dungeness crab were the endpoints at highest risk for the study area. Both are important to the mission of the PBNER. The range of species and the representation of the estuarine habitat in the Salish Sea region were important in the selection of a National Estuarine Research Reserve. Dungeness crab is an iconic species for the region.

Ballast water management scenario. Little reduction of risk (~1%) occurred when the ballast water treatment management scenario was run; the distribution patterns shifted slightly to lower scores. Many ballast water treatments are relatively new and 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 treatment efficacy were not made available to the public. Only approximately 11% to 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). Furthermore, the propagule reduction results were based on a limited volume of water ($3\,m^3$ vs the ideal volume of 30–60 m^3; Albert et al. 2010; Gollasch 2011; USEPA SAB 2011). Finally, equipment detecting smaller categories of organisms ($\leq 10\,\mu m$) is not advanced enough to produce reliable results on organism concentrations (California State Lands Commission 2013).

Although the ballast water treatment management scenario displayed little reduction of risk, we were curious as to the potential for this management option. Therefore, we ran a scenario in which we analyzed maximum propagule reduction in the management nodes and CPTs of the model. Results from this scenario indicated little change in the risk scores and distributions. This is not to say that the ballast water treatments are ineffective. The model illustrated a reduction of propagule pressure of 66.5% to 51.7% in the high state of the NIS from shipping vectors node with the management scenario. However, reductions of propagules from the management scenario did not have a substantial effect on the endpoints, suggesting that other vectors are driving the risk. In this PBNERR case study, the currents are more important to endpoint risk than ballast water exchanges, and any ballast water treatments aimed to reduce risk.

Using risk assessment in the evaluation of management options

On completing this risk assessment, we found that the effectiveness of the management options likely depends on the type of pathways of introduction. For instance, the driver of risk in the Padilla Bay case study was primarily the currents and secondary transport of NIS, and less impact was seen from shipping activities. Compared with other ports in the United States, the ports of March Point and Anacortes (adjacent to Padilla Bay) had few vessel arrivals (531) over a 3-y period (2011–2013). For perspective, Seattle/Tacoma had 5255 vessel arrivals, and the San Francisco Bay area had 6705 vessel arrivals over the same period (data from NBIC 2008). Many of

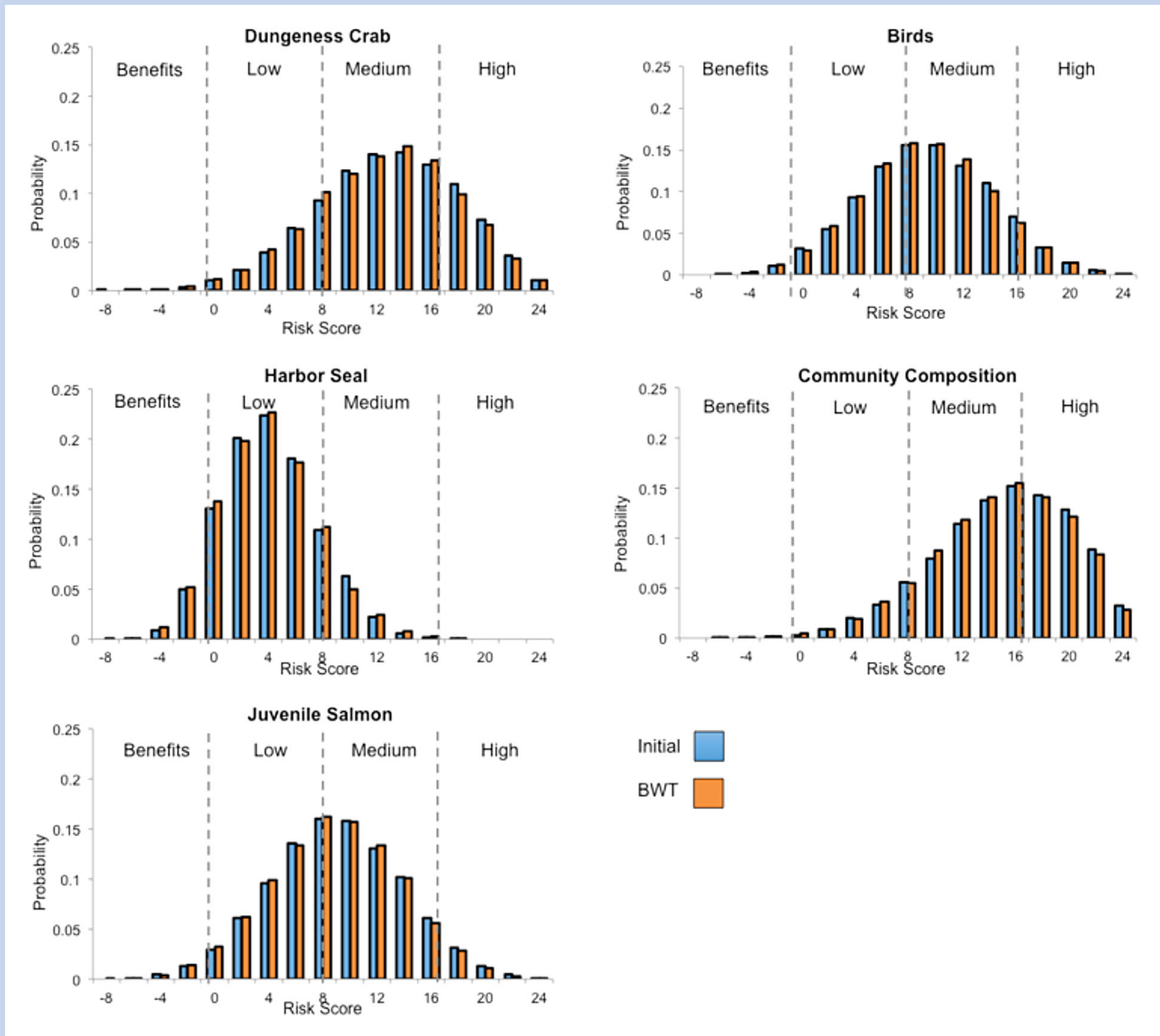

Figure 6. Distributions of initial risk estimate and comparison with the ballast water treatment scenario for each endpoint over the 4 risk regions. Dungeness crab and change to community composition were the endpoints at highest risk over the entire region. Ballast water treatment slightly altered the risk distribution for each endpoint.

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). Managers using this model may determine whether managing species through eradication once a species has settled and colonized rather than trying to prevent NIS introductions is more effective.

This modeling process is not limited to Padilla Bay; this model could be used as a template for NIS introductions in any body of water. The findings for the Padilla Bay endpoint risk 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).

Next steps

The next steps for the NIS model are to acquire data to reduce uncertainty in the model. Updating the priors (input distributions) in the model will create a more precise picture of risk to the PBNERR. Examples of such data include obtaining updated GIS data and hydrodynamic (currents and tidal flux) data. The GIS data would provide the percent coverage of vegetation in each of the risk regions, and thus the available habitat for NIS to settle. The data we currently have are from 2004, and eelgrass density can change year-to-year, especially with winter storms (Bulthuis and Shull 2006). The currents data we have are also outdated and incomplete. Understanding the movement of water into and out of Padilla Bay will help with the exposure links to the various risk regions. Finally, in our model, we did not have any data for the hull fouling node; thus, obtaining these data would reduce model uncertainty.

In addition to updating the priors of the model and reducing uncertainty, numerous ways exist to make this model more useful to decision makers. First, we could examine and incorporate other types of NIS management options into the model. Results from the sensitivity analysis showed that the currents have the greatest influence on endpoint risk. This may be a good starting point for brainstorming additional management scenarios. Incorporating these management scenarios into the model would allow decision makers to compare risk with each management option and ultimately determine the best plan of action. We could take this one step further and incorporate multiple criteria decision analysis concepts (Linkov et al. 2006) into the model and determine tradeoffs between cost and effectiveness of the treatments, and incorporate stakeholder preferences.

Finally, we would incorporate the movement of species from climate change into the model. Some NIS distributions are predicted to expand north because of warming waters (Bossenbroek et al. 2005; Hellmann et al. 2008). These shifts could influence biodiversity of 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).

CONCLUSIONS

This study has shown that we can use the BN-RRM to estimate risk from NIS introductions. We were able to determine endpoints and regions with the greatest expected risk. Furthermore, we were able to identify important findings from the model results. For instance, the sensitivity analysis indicated that the currents were the most important factor influencing endpoint risk rather than ballast water, which is what we initially expected. Finally, we were able to incorporate and evaluate a management option in the model. Although this model was unique to Padilla Bay, it could be adapted and used as a template for NIS introductions into any body of water in any part of the world.

Acknowledgment—Doug Bulthuis and Sharon Riggs from the Padilla Bay Reserve provided insight and invaluable knowledge about Padilla Bay and the native and nonindigenous 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. CEH would also like to thank her committee members, John Rybczyk and Brian Bingham, for their valuable comments on her thesis manuscript. 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.

Disclaimer—The peer review for this manuscript was managed by the Editorial Board without the involvement of WG Landis.

SUPPLEMENTAL DATA

Notes for viewing the BN models. The BN models listed below are labeled for the initial risk estimates as follows: NIS_RR_1.neta referring to Risk Region 1. The ballast water treatment management models are also included in the supplementary materials for each risk region, with NIS_RR1_-with_BW_tmt.neta corresponding to the ballast water treatment management option for Risk Region 1. The files are written in Netica™, which can be downloaded from the Norsys website (https://www.norsys.com/netica.html). Download and purchase instructions can be found on this website as well. The free version of Netica™ allows the reading and saving of models up to a certain size (15 nodes). The reading of the model includes access to the conditional probability tables for each child node. We also recommend reading the introductory tutorial at: https://www.norsys.com/tutorials/netica/nt_toc_A.htm.

NIS_RR_1
NIS_RR_1_with_BW_tmt.neta
NIS_RR_2
NIS_RR_2_with_BW_tmt.neta
NIS_RR_3
NIS_RR_3_with_BW_tmt.neta
NIS_RR_4
NIS_RR_4_with_BW_tmt.neta

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