

A qualitative network model for the management and conservation of
bull kelp (*Nereocystis luetkeana*) in Puget Sound

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Abstract

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Significant declines in the extent and density of the canopy-forming kelp *Nereocystis luetkeana* (bull kelp) have been documented within the inland waters of the Salish Sea, most notably the Puget Sound. Expert focus groups in combination with a global literature review have been used to identify the primary stressors most likely driving kelp decline in the Salish Sea in the absence of quantitative data. Qualitative network models require only a qualitative understanding of the interactions between the components of an ecological system, and can be useful management tools in data-limited situations. The goal of this project was to develop a qualitative network model to evaluate the impacts of identified stressors on bull kelp in Puget Sound, following the development of a conceptual model by Hollarsmith et al. (2022). Simulations of the model system highlight the indirect impacts of human activities on bull kelp canopy cover, the threats climate change poses to bull kelp in Puget Sound, and explore management interventions to protect and restore bull kelp.

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1 Introduction

Significant declines in the extent and density of the canopy forming kelp *Nereocystis luetkeana* (bull kelp) have been documented within the inland waters of the Salish Sea, most notably the Puget Sound (Palmer-McGee 2019; Calloway et al. 2020; Berry et al. 2021), despite relatively stable long-term population trends on the nearby outer coast of Washington, the Western edge of the Strait of Juan de Fuca, and other neighboring basins (Krumhansl et al. 2016; Pfister, Berry, and Mumford 2018; Schroeder et al. 2020; Calloway et al. 2020). Bull kelp is a foundation species in the Salish Sea (Figure 1), where it creates biogenic habitat in shallow rocky subtidal areas that is critical to many important marine species (Teagle et al. 2017; Pfister, Berry, and Mumford 2018; Shaffer, Munsch, and Cordell 2020; Calloway et al. 2020). Kelps are also important foundational components of marine food webs, serving as drivers of primary production and major producers of detritus, which connects bull kelp beds with neighboring nearshore habitats and ecological communities (Krumhansl and Scheibling 2012; Klinger 2015; Olson et al. 2019). In addition to these key ecological functions, bull kelp has been a culturally important food and source of materials to Indigenous Coast Salish peoples since time immemorial (Naar 2020). Concern surrounding declines of this important kelp species, and the potential for drivers of bull kelp decline to cause declines in other important understory kelp species, has prompted a collaborative research and management recovery agenda in Washington state (Starko et al. 2019; Calloway et al. 2020; Hollarsmith et al. 2022).

The first strategic goal established in the 2020 Puget Sound Kelp Protection and Recovery plan is an increased understanding of the stressors driving kelp decline in Puget Sound

(Calloway et al. 2020). In many regions globally the primary drivers of kelp decline are well studied and include pressures from human development and related environmental stressors (Pfister, Berry, and Mumford 2018; Karen Filbee-Dexter and Wernberg 2018; Thomas Wernberg et al. 2019; Smale 2020). Comparatively little quantitative data are available describing the impacts of these stressors on kelp within the Puget Sound and larger Salish Sea region, but expert focus groups in combination with a global literature review have been used to identify the primary stressors most likely to be driving kelp decline in the Salish Sea (Hollarsmith et al. 2022). In the absence of a more complete quantitative understanding of how these stressors impact bull kelp both individually and cumulatively, qualitative network models can be used to help scientists and managers begin to understand the complex interactions driving localized kelp decline and develop appropriate management actions.

Qualitative network models require only a qualitative understanding of the interactions between the different elements of an ecological system, and can be useful management tools in data-limited situations (Levins 1974; Puccia and Levins 1985; Reum et al. 2019). Building on a conceptual model, qualitative network models connect the elements of a system by the directional sign of the relationships between them (positive, neutral, or negative), also known as a signed directed graph (digraph), to allow for the simulation of various scenarios involving manipulations (press perturbations) of specified parts of the systems and subsequent evaluation of the response of each component of the ecological system. They have been used previously to explore alternative stable states in ecological systems (Marzloff et al. 2011), explore the consequences of invasive species eradication (Raymond et al. 2011), evaluate the potential effects of ocean acidification on a

shellfish-producing estuary (Reum et al. 2015), identify potential management interventions to rebuild a fishery collapsing under pressures from climate change (Reum et al. 2019), and assess the importance of direct effects and feedback loops for community stability in the Southern Ocean (Ward et al. 2021).

The goal of this project was to develop a qualitative network model to evaluate the impacts of both direct and indirect stressors and environmental factors on bull kelp in Puget Sound, following the development of a conceptual model for the Salish Sea by Hollarsmith et al. (2022). After developing the qualitative network model, I simulated perturbations to the system to examine how bull kelp canopy cover responds to both direct and indirect changes in the social and environmental systems of Puget Sound.

2 Methods

2.1 Conceptual Model

Understanding the interactions between ecological and societal processes is a key challenge of coastal zone management (Lewison et al. 2016). The Driver-Pressure-State-Impact-Response (DPSIR) framework is a methodology for structuring complex problems that has been used previously to develop conceptual understandings of coastal zone systems and support decision making (Tscherning et al. 2012; Lewison et al. 2016). The components of the DPSIR framework are defined as: Drivers - human activities that affect the environment (indirect stressors); Pressures - direct effects of drivers on the environment (direct stressors); State - environmental condition as a result of pressures; Impact - change in state as a result of pressure impacts ; and Response - priorities, targets, and policies adopted by

policy makers to improve undesired changes in state (Kristensen 2004; Hollarsmith et al. 2022).

Following the DPSIR framework, Hollarsmith et al. (2022) developed a conceptual model of the drivers and pressures that influence bull kelp canopy cover in the Salish Sea using a combination of expert input and literature review (Lewison et al. 2016; Hollarsmith et al. 2022). This conceptual model identified the primary human activities and environmental factors acting as stressors on nearshore kelp forest ecosystems, and the linkages between them (Figure 2), and is the first step towards the development of a qualitative network model.

2.2 Qualitative Network Model

I used the conceptual model and literature review from Hollarsmith et al. (2022) to create a signed directed graph (digraph) of the system (Figure 3). This signed digraph shows the structure of the Puget Sound bull kelp qualitative network model, which I used to evaluate the impacts of changes to both direct and indirect stressors on bull kelp canopy cover in Puget Sound. Community components of the system (bull kelp canopy cover, biotic and abiotic ecosystem components, and human activities) are represented in the model as boxed nodes (described in Table 1), which are connected by linkages (edges) denoting the sign (positive, neutral, or negative), of the direct effects of interactions between nodes. Linkages convey only the direction of these effects, not the magnitude of change.

In both the conceptual model and this qualitative network model, system components are divided into three categories adapted from the DPSIR framework: direct impacts (Pressures), indirect impacts (Drivers), and bull kelp canopy cover (State). Direct impacts in

the model are biotic and abiotic ecosystem components that have a direct influence on each other and on bull kelp canopy cover. Direct impacts include contaminants, temperature, light penetration, benthic sedimentation, salinity, nutrients, herbivores, epiphytes, and algal competitors. Indirect impacts are primarily human activities managed at the local scale that do not directly impact bull kelp canopy cover but do influence other relevant ecosystem components. These include dredging, vessel traffic, upland development, shoreline development, and impacts on trophic structures represented here as predatory fish abundance. Bull kelp canopy cover, the environmental state being examined in this model, refers to the habitat-forming adult sporophyte life stage of *Nereocystis luetkeana*. The majority of studies identified in the development of the conceptual model focused primarily on the adult sporophyte life stage of bull kelp (Hollarsmith et al. 2022). Agreement between the direction of impact when directional relationships were supported by studies on multiple life stages suggests that these results may be cautiously extrapolated to other stages, but this model does not otherwise address the spore, gametophyte, and microscopic sporophyte life stages of bull kelp. Growth rates and environmental challenges may differ between life stages (Dobkowski and Crofts 2021), and further research is needed for a better understanding of how the stressors present in this model affect the full bull kelp life cycle.

Analysis of the qualitative network model was performed using the QPress package in R (Melbourne-Thomas et al. 2012), based on a community matrix of interaction coefficients translated from the signed digraph (Levins 1974; Puccia and Levins 1985). To simulate the response of each component of the system, a large number of community matrices with randomly assigned edge weights were created until 10^4 stable matrices, checked against

system stability criteria, were retained (Melbourne-Thomas et al. 2012; Reum et al. 2019; Ward et al. 2021). The result of these simulations is the proportion of simulated stable matrices in which each named node had a negative or positive response to a press perturbation (a manipulation of a node, either up or down) of a particular node or set of nodes. In some simulation scenarios, multiple press perturbations may be performed on multiple nodes concurrently to represent the cumulative impacts of the scenario in question. The agreement between these simulations can then be used to describe an estimate of the certainty of these responses as predicted by the model. Responses with >80% sign agreement (positive or negative) are considered highly certain, responses with 60-80% sign agreement are considered moderately certain, and responses with <60% sign agreement were considered uncertain or inconsistent (Raymond et al. 2011; Harvey et al. 2016; Reum et al. 2019). An uncertain or inconsistent response could indicate a potential priority for further research, because additional quantitative data would be needed to confidently predict how that node may respond to a given scenario.

2.3 Press Perturbation Scenarios

I evaluated the response of bull kelp canopy cover to 15 simulation scenarios in three categories: indirect impacts (human activities), direct impacts (through several climate change scenarios), and a management scenario (the implementation of a kelp sanctuary). Manipulated (pressed) nodes for each category are indicated in Table 2.

2.3.1 Indirect Impacts: Human activities managed at the local scale

I simulated six scenarios to evaluate the response of bull kelp canopy cover to the indirect impacts represented in the model. These human activities managed at a local scale and their impacts on kelp have been identified as priorities for research within the Salish Sea (Hollarsmith et al. 2022). Scenarios 1a - 1d represent positive press perturbations on dredging, vessel traffic, upland development and shoreline development, respectively. Scenario 1e represents a negative press perturbation on predatory fish abundance, to reflect human impacts on trophic structures that may be releasing herbivores from predation pressure (Dunn, Baskett, and Hovel 2017; Calloway et al. 2020). Scenario 1f represents each of these press perturbations applied simultaneously.

2.3.2 Direct Impacts: Climate change scenarios

Nodes with direct impacts on bull kelp canopy cover were evaluated through a series of three climate change scenarios: ocean warming, ocean warming combined with ocean acidification, and a more comprehensive scenario representing all of the climate-change related pathways identified by Hollarsmith et al. (2022).

The physical characteristics of the Puget Sound Basin can create localized environmental conditions that have the potential to influence the impact and intensity of stressors on kelp beds in different areas of Puget Sound, as has been observed in other parts of the Salish Sea (Moore et al. 2008; Sutherland et al. 2011; Starko et al. 2019; Berry et al. 2021). An increased understanding of the impact of these sub-regional differences on kelp and kelp stressors is identified as a suggested action in the Puget Sound Kelp Recovery Plan (Calloway et al. 2020). Within Puget Sound, the presence of shallow sills can create strong

tidal mixing that distributes nutrients throughout the water column, with the exception of areas near river mouths or far from sills where vertical stratification and deep pycnoclines can occur between 4 and 10 m depth (Moore et al. 2008; MacCready et al. 2021). As a first attempt at using the model to examine the impacts of these regional differences on bull kelp canopy cover, I simulated these three climate scenarios in both mixed and stratified environments, for a total of six scenarios in this category. In representations of stratified environments, both salinity and nutrients were subject to a negative press perturbation to reflect reduced mixing and increased stratification conditions in addition to presses related to the climate scenario.

In scenarios 2a and 2b, temperature was subject to a positive press perturbation to reflect ocean warming in mixed and stratified environments, respectively. Scenarios 2c and 2d represent a positive press perturbation to temperature in addition to negative press perturbations to herbivores and epiphytes to simulate the additional impacts of ocean acidification on herbivores and epiphytes with calcium carbonate structures (Orr et al. 2005; Doney et al. 2009; Feely et al. 2010; Campbell and Fourqurean 2014; Bednaršek et al. 2021). Scenarios 2e and 2f represent the comprehensive climate scenario, in which I implemented positive press perturbations on temperature and contaminants and negative press perturbations on benthic sedimentation, light penetration, salinity, herbivores, and epiphytes to reflect all of the climate-change related pathways identified by Hollarsmith et al. (2022).

2.3.3 Management Scenario: Kelp sanctuary

Qualitative network models can be used to simulate the impacts of potential management actions in data-limited situations. In these scenarios I used the model to evaluate the impacts of one management action, a kelp protected area, on bull kelp canopy cover. The designation of kelp protected areas is a goal described within the 2020 Puget Sound Kelp Recovery Plan (Calloway et al. 2020). In January of 2022 the Washington State Legislature passed Senate Bill 5619, directing funding to the Washington Department of Natural Resources for the development of a Kelp Forest and Eelgrass Meadows Health and Conservation Plan and establishing a goal to conserve and restore at least 10,000 acres of kelp forests and eelgrass meadows by 2040 (Lovelett et al. 2022). In March 2022 the first of these protected areas was established near the mouth of the Snohomish River, preventing development within the protection zone for the next 50 years (Figure 1) (Washington State Department of Natural Resources 2022).

I simulated three scenarios reflecting the designation of a kelp protected area. Scenario 3a reflects negative press perturbations to shoreline development and dredging, representing the cessation of activities prohibited within the protection zone. Scenarios 3b and 3c represent the effects of a kelp protected zone under the comprehensive climate change scenario from the previous section in mixed and stratified environmental conditions, respectively.

3 Results

3.1 Indirect Impacts: Human activities managed at the local scale

In most simulated stable matrices, results indicated with high certainty that bull kelp canopy cover responded negatively to positive press perturbations on nodes representing human activities managed at the local scale (Figure 4). Bull kelp responded negatively in 100% of simulations representing increases in dredging and vessel traffic (Scenario 1a and 1b), 83.99% of simulations representing an increase in upland development (Scenario 1c), 80.61% of simulations representing a decrease in predatory fish abundance (Scenario 1e), and 84.69% of simulations representing each of these press perturbations to human activity nodes applied simultaneously (Scenario 1f). Scenario 1d, a positive press on shoreline development, was the exception to this pattern; with moderate certainty, bull kelp canopy cover responded positively in 69.81% of simulations.

Model results support the contention that the impacts of these human activities move through the ecological system to indirectly impact bull kelp. These patterns are mostly consistent with increasing trends of urbanization and development and documented losses of kelp canopy cover in the Puget Sound region over approximately the past 150 years (Berry et al. 2021). In the exception to these patterns, Scenario 1d which reflected a positive press on shoreline development, both light penetration and nutrients also responded positively in 100% of scenarios. Both of these factors are critical to kelp growth and development (Dayton 1985; Pfister, Berry, and Mumford 2018), and their positive response may be playing a role in the observed positive response of bull kelp to an increase in shoreline development in the model simulation.

3.2 Direct Impacts: Climate change scenarios

Bull kelp canopy cover showed a negative response with high certainty to every scenario in this category (Figure 5). Bull kelp responded negatively in 100% of simulations representing ocean warming in a mixed environment (Scenario 2a), 97.33% of simulations representing ocean warming in a stratified environment (Scenario 2b), 92.45% of simulations representing ocean acidification in a mixed environment (Scenario 2c), 96.96% of simulations representing ocean acidification in a stratified environment (Scenario 2d), 91.51% of simulations representative the comprehensive climate scenario in a mixed environment (Scenario 2e), and 92.37% of simulations representing the comprehensive climate scenario in a stratified environment (Scenario 2f).

No notable differences in the response of bull kelp canopy cover were observed between the simulated mixed and stratified areas. It is possible that mixing and stratification may not play a strong role in these particular scenarios, or that the model in its current form may not be resolving localized differences at this scale. The response of algal competitors did show noticeable differences between mixed and stratified areas, with positive responses of medium and high certainty in mixed scenarios and either negative or highly uncertain responses in stratified areas.

3.3 Management Scenario: Kelp Sanctuary

Bull kelp canopy cover responded positively to the majority of simulations in this category, although only Scenario 3a, negative press perturbations to shoreline development and dredging, showed a moderately certain response with 76.76% of simulations resulting in a positive response from bull kelp (Figure 6). The results of Scenario 3b, which represented

negative press perturbations on shoreline development and dredging in addition to the comprehensive climate scenario in a mixed environment, were nearly consistent with 59% of simulations resulting in a positive response. 53.35% of simulations showed a positive response in Scenario 3c, representing negative press perturbations on shoreline development and dredging and the comprehensive climate scenario in a stratified environment.

The response of bull kelp canopy cover in this category was, by comparison, the least certain but most consistently positive of the three scenario categories. The results of simulations in this category suggest that the implementation of kelp sanctuary areas may be a useful conservation and restoration tool to increase bull kelp canopy cover, with some indication that climate change and the impact of environmental factors outside the scope of sanctuary management will complicate the rate of success.

4 Discussion

The results of the simulated scenarios using the Puget Sound bull kelp qualitative network model reveal three key findings. First, in each scenario the indirect impacts of human activities moved through the model system and ultimately had an impact on bull kelp canopy cover. Second, simulation results suggest that climate change poses risks to bull kelp cover in Puget Sound, potentially across regional oceanographic differences in mixing and stratification. Third, the positive response of bull kelp canopy cover to a simulated increase in shoreline development was unexpected, and the mechanisms driving this

response may warrant further investigation. This initial qualitative network model can be adapted to more specific questions and used to evaluate different management actions.

Anthropogenic activities including urbanization, logging, agriculture, and industrial activity have been associated with changes to coastal marine systems and regional trends of kelp decline (Thomas Wernberg et al. 2019; Berry et al. 2021; Hollarsmith et al. 2022). In five out of six simulation scenarios evaluating the response of bull kelp canopy cover to the indirect impacts of human activities represented in the model, an increase in these indirect stressors moved throughout the model system and resulted in a decrease in bull kelp canopy cover. These results are generally consistent with other studies that have described localized kelp decline following increases in coastal development and industrial activities (Karen Filbee-Dexter and Wernberg 2018; Thomas Wernberg et al. 2019). These actions and their influences on trophic structures and kelp forest communities within the Salish Sea have been identified as research priorities to support management decision making (Hollarsmith et al. 2022). It has also been suggested that reducing the impacts of local anthropogenic activities may be an effective strategy to prevent further kelp decline (Karen Filbee-Dexter and Wernberg 2018). While model results suggested with high confidence that increasing vessel traffic would result in decreased bull kelp canopy cover, both the conceptual model and qualitative network model notably do not yet include the direct impacts of waves and currents, which influence kelp distributions and morphology (Hurd 2000; Thomas Wernberg et al. 2019; Starko et al. 2019; Berry et al. 2021; Dobkowski and Crofts 2021). Ferry wakes in British Columbia have been shown to increase species richness, overall abundance, and primary production of intertidal seaweeds (Demes, Kordas, and Jorve 2012). In parts of Puget Sound, persistent bull kelp beds have been

associated with high current flows (Berry et al. 2021). Further consideration of the connection between vessel traffic and wave action, and the inclusion of these relationships in the model, would provide a more complete understanding of the impacts of this activity on bull kelp in Puget Sound.

Climate change, including warming sea temperatures, have also been identified as significant anthropogenic threats to nearshore kelp forests, as temperature is an important environmental factor in kelp growth and range distribution (Lüning 1990; Straub, Thomsen, and Wernberg 2016; Thomas Wernberg et al. 2019; Smale 2020). Bull kelp canopy cover responded negatively in every climate change scenario evaluated using the qualitative network model, which is generally consistent with observations of kelps decline following periods of increased sea temperatures such as marine heatwaves (K. Filbee-Dexter, Feehan, and Scheibling 2016; T. Wernberg et al. 2016). Significant declines in bull kelp canopy cover following a marine heatwave have been observed along northern California shorelines, where surface kelp canopy area declined by more than 90% after heatwaves between 2014 and 2016 (Rogers-Bennett and Catton 2019). Warmer sea temperatures have been associated with both decreased bull kelp abundance in British Columbia (Foreman 1984) and the disappearance of historical bull kelp beds in Puget Sound (Berry et al. 2021). While the climate change simulation scenarios tested here incorporated one component of localized oceanographic conditions, nutrient mixing and stratification, this distinction did seem to have an effect on the response of bull kelp canopy cover to simulated increasing climate change conditions. The diversity of local conditions between Puget Sound sub-basins will likely affect the sensitivity of kelp beds to climate change impacts (Berry et al. 2021). A more thorough consideration of specific habitat

characteristics and fine-scale oceanographic conditions within the model may result in more accurately tailored predictions of climate change impacts on local-scale bull kelp beds in Puget Sound (Starko et al. 2019).

While most model results related to anthropogenic stressors were consistent with previous evidence, the positive response of bull kelp canopy cover to a simulated increase in shoreline development (Scenario 1d) was unexpected. In both the conceptual model and qualitative model, shoreline development includes two kinds of activity: shoreline armoring and over- and near water construction of docks and other structures (Hollarsmith et al. 2022). The immediate impacts of these activities are generally interpreted as stressors on nearshore kelp ecosystems due to construction activity, shading (Szypulski 2018), contaminants (Antrim et al. 1995), and association with dredging and increased vessel traffic. The results of the qualitative network model simulation show an eventual new equilibrium state following the initial disturbance of the press perturbation. When an increase in shoreline development was combined with increases in additional anthropogenic stressors in Scenario 1f, the simulated response of bull kelp canopy cover was negative. Scenarios 1a - 1e evaluated the response of bull kelp canopy cover to increases in human activities individually, but as increases in shoreline development rarely, if ever, occur absent of other anthropogenic stressors this scenario may need to be adjusted to more closely examine the relationship between shoreline development and bull kelp. This may include separating shoreline armoring from over- and near- water construction and making a distinction between marine-derived nutrients and anthropogenic nutrients for a more targeted response.

The relationship between bull kelp and shoreline development was also evaluated in the context of a simulated management scenario, the implementation of a kelp sanctuary area where shoreline development and dredging are prohibited (Scenarios 3a - 3c). When combined with a decrease in dredging, simulated decreases in shoreline development resulted in a positive response from bull kelp canopy cover. This result underscores the importance of considering potential stressors on nearshore kelps in more comprehensive scenarios and in combination with each other. This initial model can be adapted to examine different management actions, develop hypotheses, and evaluate and identify gaps in our understanding that can subsequently be evaluated through targeted quantitative data collection.

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Tables

Table 1. Basic description of each node in the qualitative network model.

| Node | Description |
|--------------------------|---|
| Algal competitors | Understory native and invasive algal species |
| Benthic sedimentation | Benthic sediment accumulation |
| Bull kelp canopy cover | Measure of bull kelp canopy, extrapolated to all life stages |
| Contaminants | Contaminants including heavy metals, sewage, and petrochemicals |
| Dredging | Removal of benthic sediment, common practice in Salish Sea ports |
| Epiphytes | Epiphyte growth on kelp and other species |
| Herbivores | Crustaceans, sea urchins, snails |
| Light penetration | Light penetration, as affected by water clarity |
| Nutrients | Nutrient concentration in the water column, especially Nitrogen |
| Predatory fish abundance | Reflective of the trophic effects of regional fishing, past and present |
| Salinity | Salinity |
| Shoreline development | Shoreline hardening, over- and near- water structures including docks |
| Temperature | Sea surface temperature |
| Upland development | Logging, agriculture, urbanization, dams, industrial development |
| Vessel traffic | Recreational and commercial vessel traffic, small and large vessels |

Table 2. Summary of the scenarios examined using the Puget Sound bull kelp qualitative network model. For each scenario, manipulated (press) variables and direction of press (either up + or down -) are indicated.

| Scenario category | Scenario | Press variable(s) and direction (+ / -) |
|--|----------|---|
| Indirect impacts: Human actions managed at the local scale | 1a | Dredging (+) |
| | 1b | Vessel traffic (+) |
| | 1c | Upland development (+) |
| | 1d | Shoreline development (+) |
| | 1e | Predatory fish abundance (-) |
| | 1f | Dredging (+), Vessel traffic (+), Upland development (+), Shoreline development (+), Predatory fish abundance (-) |
| Direct impacts: Climate change scenarios | 2a | Temperature (+) |
| | 2b | Temperature (+), Nutrients (-), Salinity (-) |
| | 2c | Temperature (+), Herbivores (-), Epiphytes (-) |
| | 2d | Temperature (+), Herbivores (-), Epiphytes (-), Nutrients (-), Salinity (-) |
| | 2e | Contaminants (+), Benthic sedimentation (-), Light penetration (-), Temperature (+), Salinity (-) |
| | 2f | Contaminants (+), Benthic sedimentation (-), Light penetration (-), Temperature (+), Salinity (-), Nutrients (-) |
| Management scenario: Marine vegetation sanctuary | 3a | Shoreline development (-), Dredging (-) |
| | 3b | Shoreline development (-), Dredging (-), Contaminants (+), Benthic sedimentation (-), Light penetration (-), Temperature (+), Salinity (-) |
| | 3c | Shoreline development (-), Dredging (-), Contaminants (+), Benthic sedimentation (-), Light penetration (-), Temperature (+), Salinity (-), Nutrients (-) |

Figures

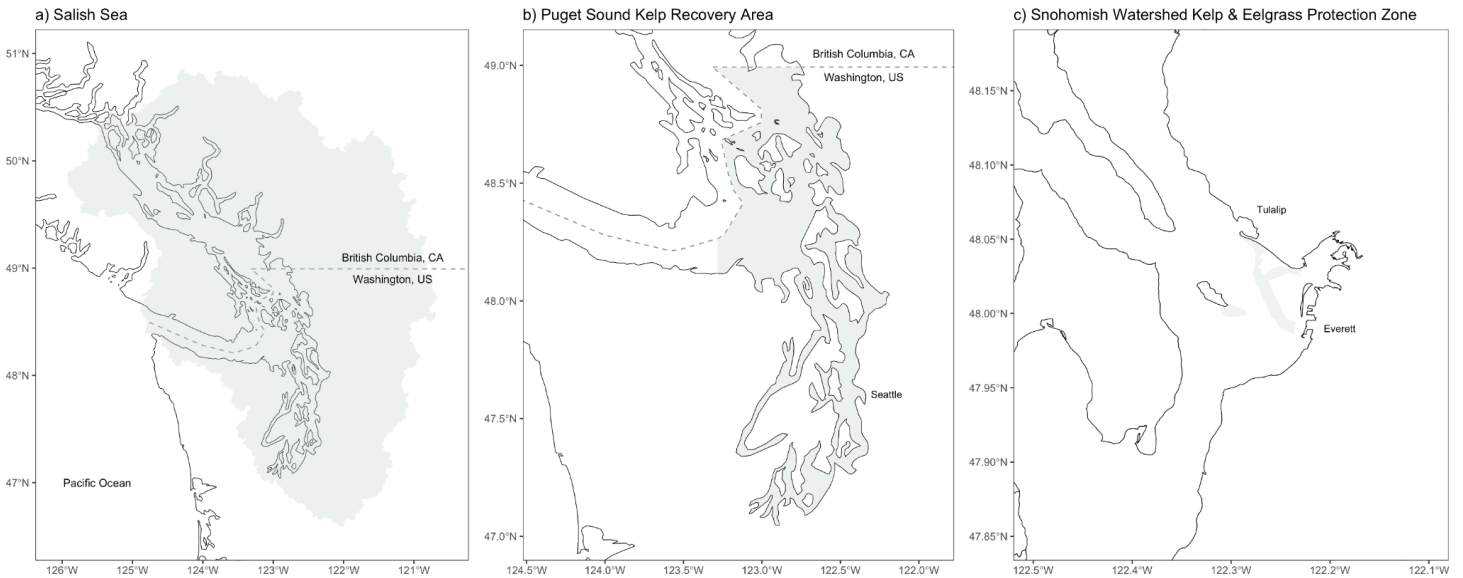


Figure 1. Three panel map highlighting a) the larger Salish Sea Area, b) the Puget Sound Kelp Conservation Recovery Area, and c) the Snohomish Watershed Kelp and Eelgrass Protection Zone.

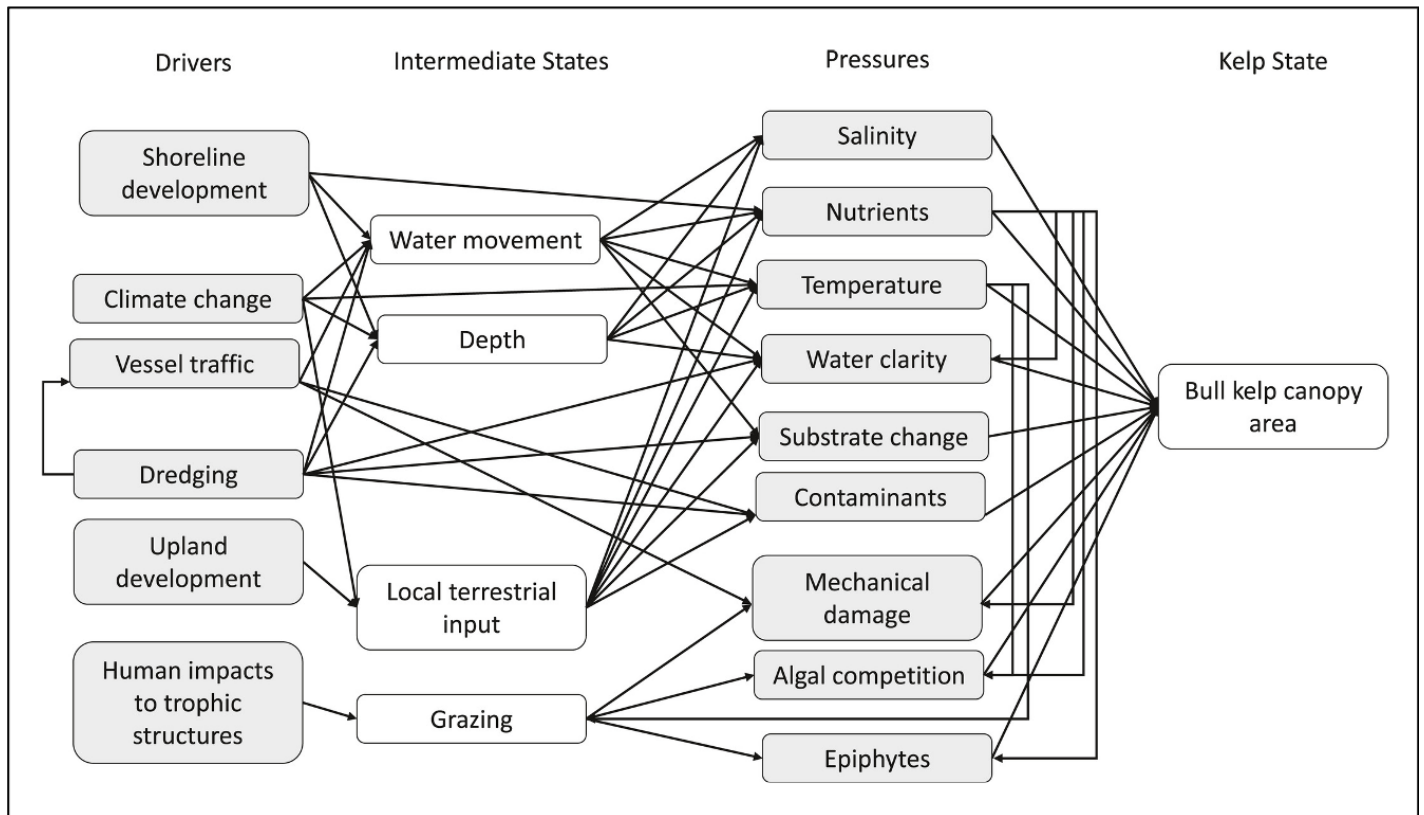


Figure 2. Conceptual model of drivers and pressures impacting kelp from Hollarsmith et al. 2022.

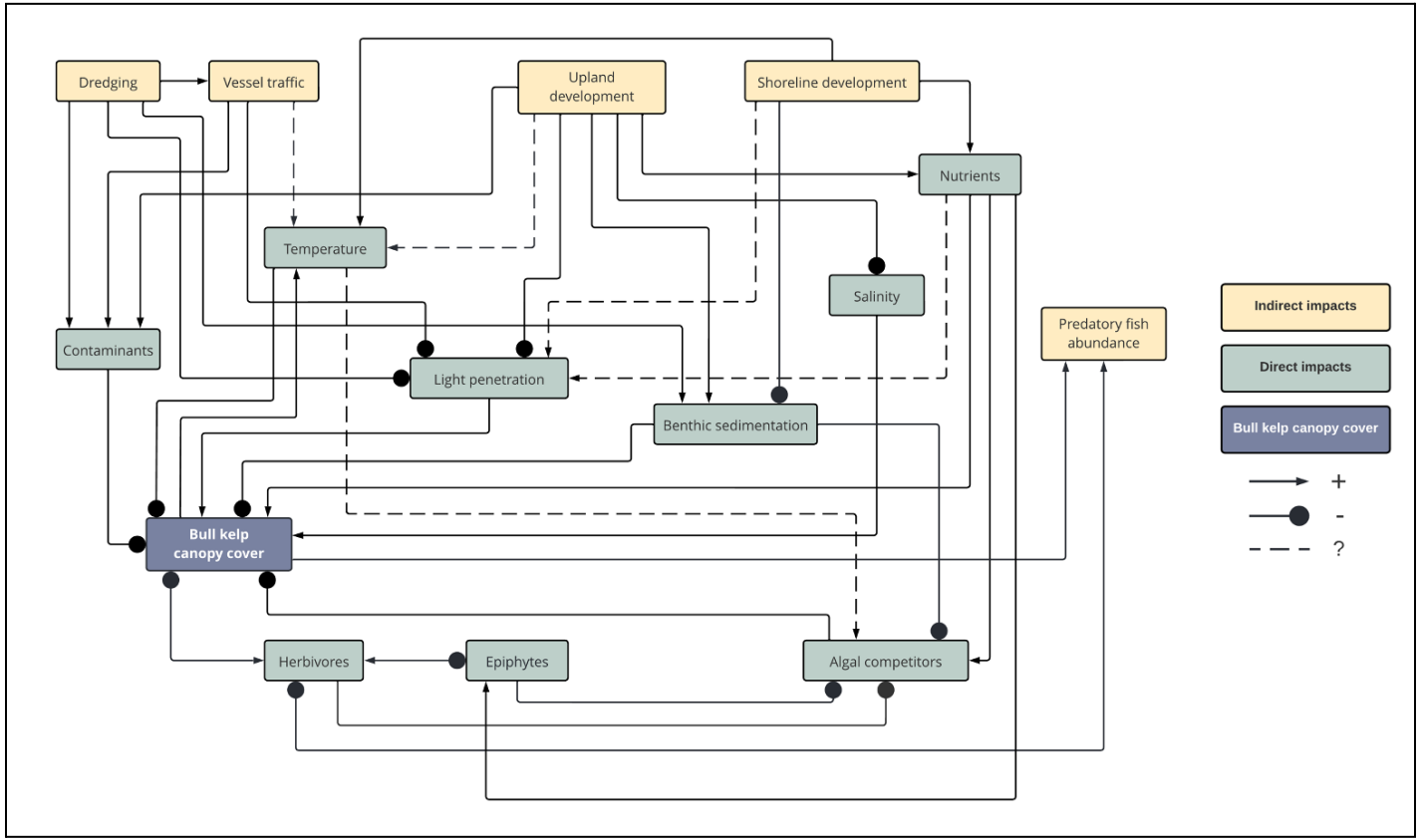


Figure 3. Qualitative interaction network for bull kelp (*Nereocystis luetkeana*) canopy cover in Puget Sound, Washington. Components of the system are represented by boxed nodes and grouped together in three categories; indirect impacts are human activities managed at the local scale (yellow), direct impacts are biotic and abiotic ecosystem components (light green), and bull kelp canopy cover (dark blue). Linkages between nodes terminating in an arrow indicate a positive influence, linkages terminating in a filled circle indicate a negative influence, and linkages with both an arrow and a filled circle indicate a predator-prey relationship. All nodes have a limiting (negative) self interaction, which is not shown here. Dashed lines indicate linkages that were supported by two or fewer studies in the development of the conceptual model.

Scenario Category 1: Direct Impacts

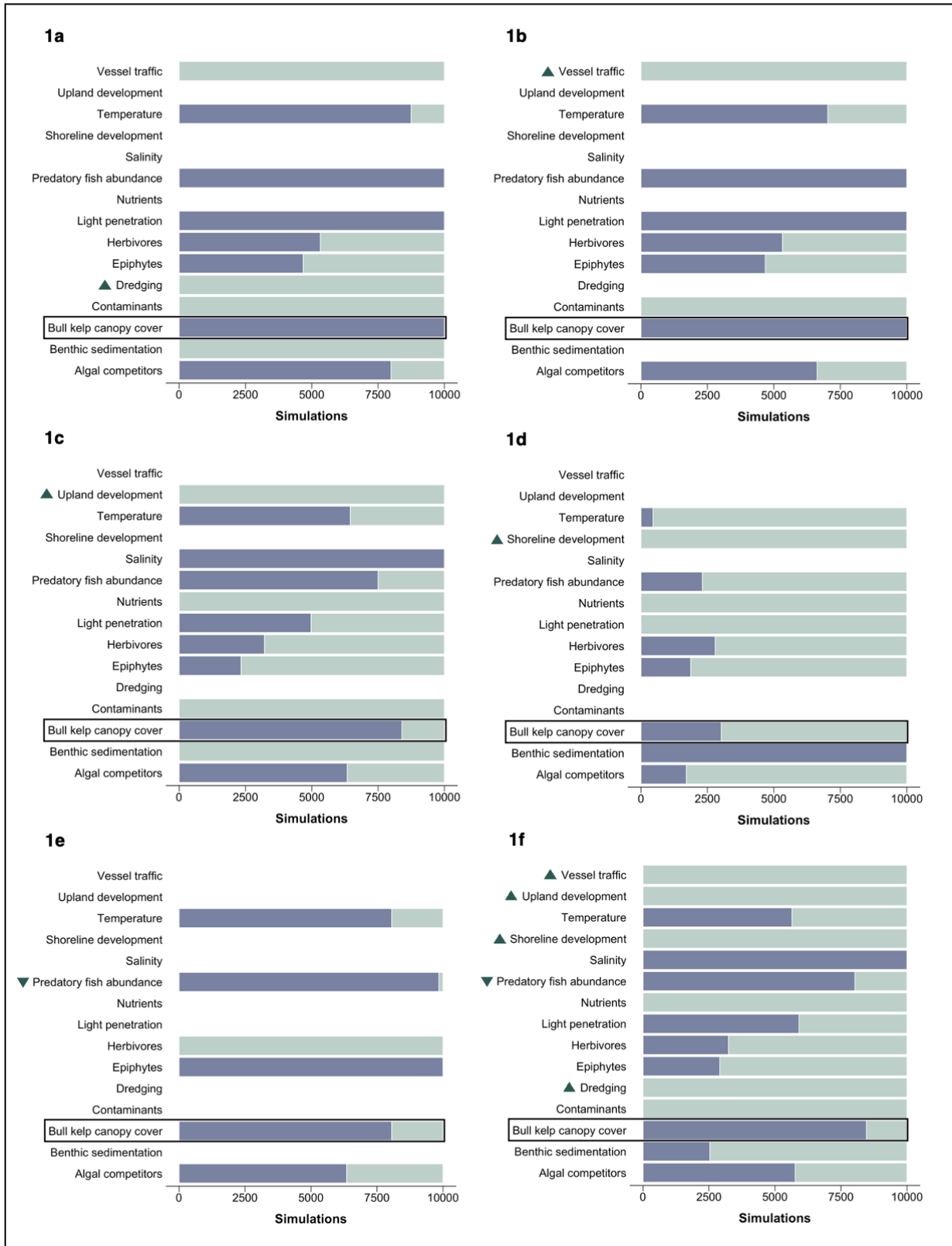


Figure 4. Simulation outcomes from the Puget Sound bull kelp QNM in response to a positive press perturbation to dredging (1a), vessel traffic (1b), upland development (1c), shoreline development (1d), predatory fish abundance (1e), and all of the previously listed nodes together (1f). The proportion of simulated stable matrices in which each named node had a negative response to the press perturbation is shown in dark blue, while positive responses are shown in light green. For each perturbation the response of bull kelp canopy cover is highlighted with a black box, and the pressed variable direction of the perturbation is indicated with a triangle.

Scenario 2: Indirect Impacts, Climate Change

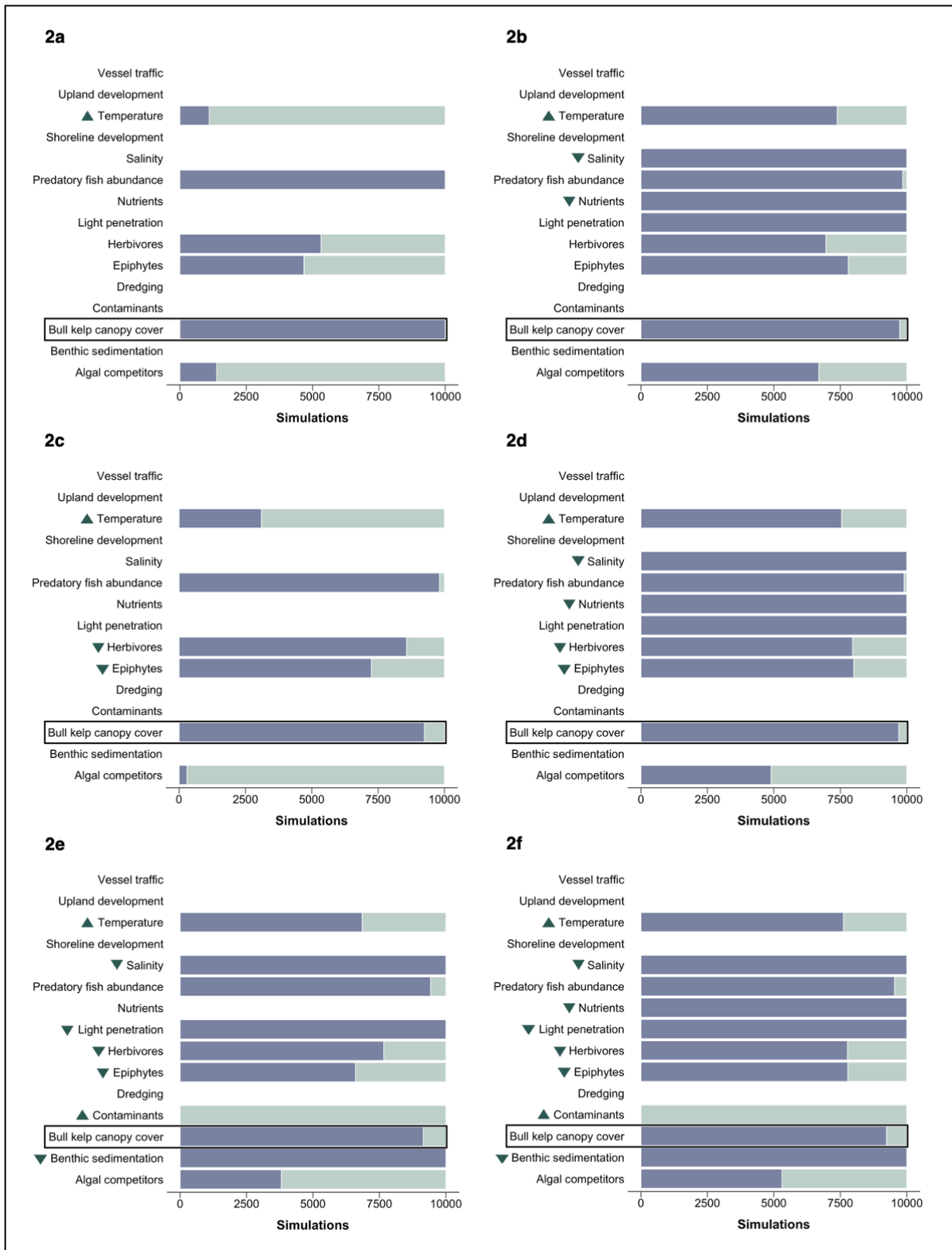


Figure 5. Simulation outcomes from the Puget Sound bull kelp QNM in response to press perturbations of direction stressors to reflect climate change scenarios in both well mixed (2a, 2c, and 2e) and stratified (2b, 2d, and 2f) areas of Puget Sound. The proportion of simulated stable matrices in which each named node had a negative response to the press perturbation is shown in dark blue, positive responses are shown in light green. For each perturbation the response of bull kelp canopy cover is highlighted with a black box, and the pressed variable direction of the perturbation is indicated with a triangle.

Scenario 3: Management Scenario (Kelp Sanctuary)

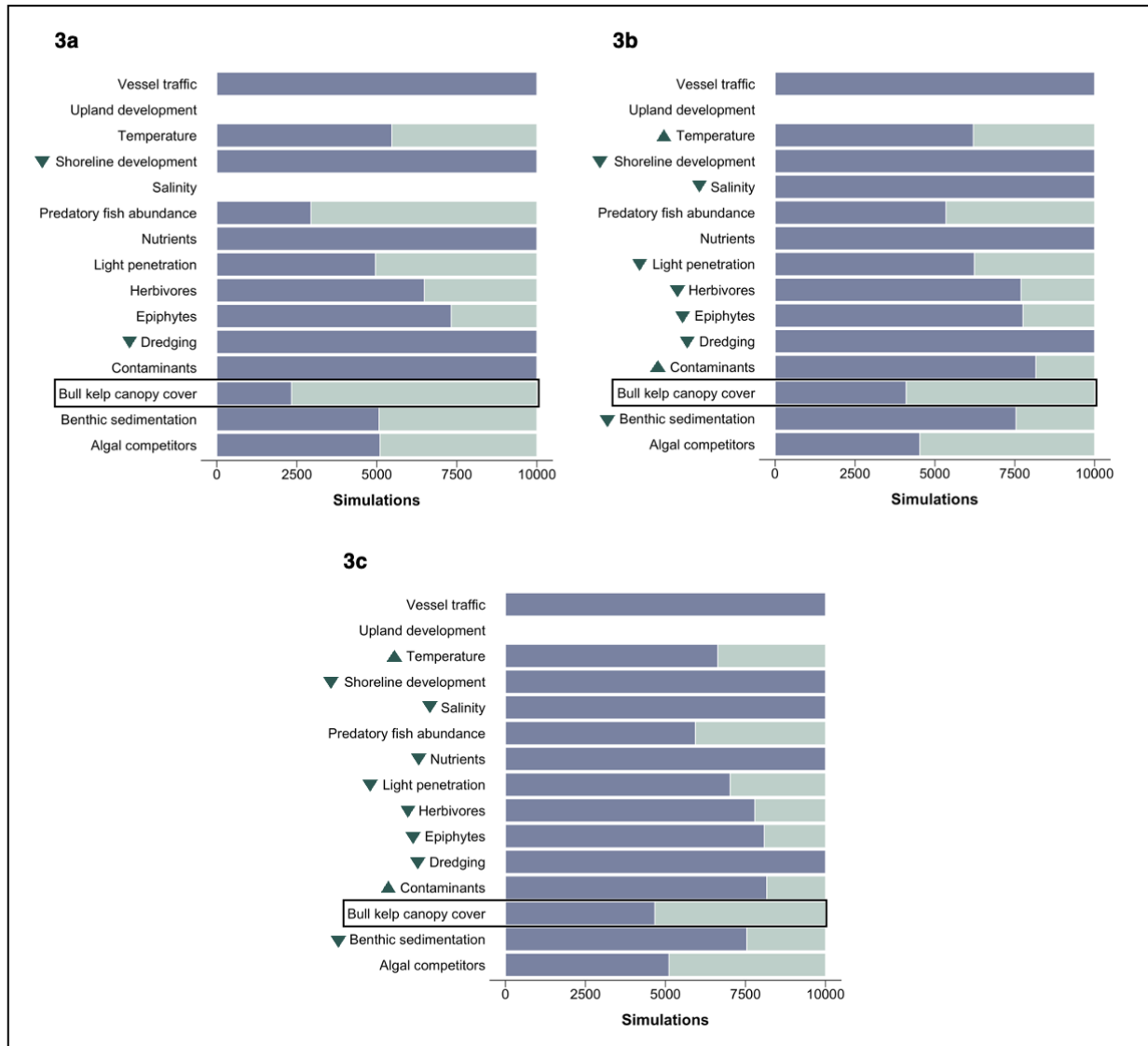


Figure 6. Simulation outcomes from the Puget Sound bull kelp QNM in response to press perturbations of direct stressors to reflect the implementation of a marine vegetation protected area under status quo (3a) and increasing climate change conditions in both mixed (3b) and stratified (3c) areas of Puget Sound. The proportion of simulated stable matrices in which each named node had a negative response to the press perturbation is shown in dark blue, positive responses are shown in light green. For each perturbation the response of bull kelp canopy cover is highlighted with a black box, and the pressed variable direction of the perturbation is indicated with a triangle.