Special Section

Estimating Effects of Tidal Power Projects and Climate Change on Threatened and Endangered Marine Species and Their Food Web

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Abstract: *Marine hydrokinetic power projects will operate as marine environments change in response to increased atmospheric carbon dioxide concentrations. We considered how tidal power development and stressors resulting from climate change may affect Puget Sound species listed under the U.S. Endangered Species Act (ESA) and their food web. We used risk tables to assess the singular and combined effects of tidal power development and climate change. Tidal power development and climate change posed risks to ESA-listed species, and risk increased with incorporation of the effects of these stressors on predators and prey of ESA-listed species. In contrast, results of a model of strikes on ESA-listed species from turbine blades suggested that few ESA-listed species are likely to be killed by a commercial-scale tidal turbine array. We applied scenarios to a food web model of Puget Sound to explore the effects of tidal power and climate change on ESA-listed species using more quantitative analytical techniques. To simulate development of tidal power, we applied results of the blade strike model. To simulate environmental changes over the next 50 years, we applied scenarios of change in primary production, plankton community structure, dissolved oxygen, ocean acidification, and freshwater flooding events. No effects of tidal power development on ESA-listed species were detected from the food web model output, but the effects of climate change on them and other members of the food web were large. Our analyses exemplify how natural resource managers might assess environmental effects of marine technologies in ways that explicitly incorporate climate change and consider multiple ESA-listed species in the context of their ecological community.*

Keywords: ocean acidification, Puget Sound, renewable energy, risk assessment, trophic interactions

Estimación de los Efectos de Proyectos de Energía de las Mareas y el Cambio Climático sobre Especies Marinas Amenazadas y en Peligro y su Red Alimentaria

Resumen: *Los proyectos de poder hidrocinético marino operarán a la vez que los cambios en los ambientes marinos responden al incremento en las concentraciones de dióxido de carbono en la atmósfera. Consideramos el efecto del desarrollo de la energía de las mareas y los estresantes que resultan del cambio climático sobre las especies de la sonda de Puget que están enlistadas en el Acta Estadunidense de Especies en Peligro (ESA) y a su red alimentaria. Usamos tablas de riesgo para analizar los efectos individuales y combinados del desarrollo de energía de las mareas y el cambio climático. El desarrollo de energía de las mareas y el cambio climático son riesgos para las especies enlistadas en la ESA, y el riesgo incrementa con la incorporación de los efectos de estos estresantes sobre las presas y depredadores de las especies enlistadas. En contraste, los resultados de un modelo de golpeo de cuchillas de turbinas sobre especies enlistadas en la ESA sugirieron que pocas de estas especies tengan la probabilidad de morir en una colección de escala comercial por turbinas de marea. Aplicamos escenarios a un modelo de red alimentaria de la sonda de Puget para explorar los efectos de energía de las mareas y el cambio climático sobre especies enlistadas en la ESA*

usando más técnicas de análisis cuantitativo. Para simular el desarrollo de energía de las mareas aplicamos los resultados del modelo de golpes de cuchilla. Para simular los cambios ambientales de los próximos 50 años aplicamos escenarios de cambio en la producción primaria, la estructura comunitaria del plancton, el oxígeno disuelto, la acidificación oceánica y los eventos de inundación de agua dulce. No se detectaron efectos del desarrollo de energía de las mareas sobre las especies enlistadas a partir de la información del modelo de la red alimentaria pero los efectos del cambio climático sobre ellos y otros miembros de la red fueron amplios. Nuestros análisis ejemplifican cómo los administradores de recursos naturales pueden estudiar los efectos ambientales de las tecnologías marinas de forma que explícitamente incorporen el cambio climático y consideren muchas especies enlistadas en la ESA en el contexto de su comunidad ecológica.

Palabras Clave: acidificación oceánica, energía renovable, estudio de riesgo, interacciones tróficas, sonda de Puget

Introduction

Reliance on fossil fuels has increased the atmospheric concentration of carbon dioxide, which affects marine species through climate change and ocean acidification (hereafter grouped under the term *climate change*) (IPCC 2007; NRC 2010). To meet growing energy needs without increasing carbon emissions, utility companies are turning to renewable energy resources such as solar, wind, tidal, and wave energy. The ecological consequences of harnessing these resources are largely unknown and rely heavily on expert opinion, especially for hydrokinetic energy (Boehlert & Gill 2010; Polagye et al. 2011). Moreover, as tidal power projects come online, their effects will occur against the backdrop of a changing climate (Ainsworth et al. 2011).

Evaluating the potential risk to species from marine energy operations and other infrastructure based on new technologies in the context of climate change presents a challenge to natural resource managers required to assess their environmental effects. Section 7 of the U.S. Endangered Species Act (ESA) requires consultation with the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA Fisheries) or the U.S. Fish and Wildlife Service to determine how proposed actions might affect ESA-listed species or their critical habitat, with NOAA Fisheries handling consultations for most marine species. Risk can be determined in a variety of ways from qualitative assessments of risk and checklists to quantitative estimates of mortality (Linkov et al. 2009). Recognizing that a changing climate will alter environmental conditions, NOAA Fisheries is exploring ways to incorporate climate change into consultations that move beyond general information on large-scale forecasts.

We assessed the potential risk from tidal power projects and climate change to marine and anadromous ESA-listed species that inhabit Puget Sound, Washington (Table 1). Puget Sound is a fjordal estuary conducive to tidal power development, which could range from pilot projects with a small number of turbines to commercial arrays of up to 100 turbines (Polagye et al. 2011). We developed 2 approaches to examine the effects of tidal power on ESA-listed species in the context of climate change. First, we constructed qualitative risk tables to evaluate the risk from tidal power implementation to ESA-listed species in Puget Sound. This technique for evaluating risk is commonly used in Section 7 consultations, especially when determining risk based on incomplete or qualitative information (Good et al. 2003). We extended these standard risk tables to consider changes in baseline risk due to climate change and to food web interactions by incorporating risk assessments of predators and prey of ESA-listed species. Doing the latter allowed us to evaluate how consideration of trophic interactions may affect risk assessment. Second, we coupled a turbine blade-strike model with a mass-balanced, food web model of Puget Sound's central basin (Harvey et al. 2010; Harvey et al. 2012). With this approach, we estimated the additional annual mortality on vulnerable functional groups caused by blade strikes and examined how the abundance of threatened and endangered species (and other functional groups) may change in response to both tidal power projects and climate change. Results of these analyses should improve understanding of whether the effects of tidal power on ESA-listed species could be detected when the effects of climate change are considered. They also should give resource managers insight into potential ecosystem-wide effects of climate change, tidal power development, and their interactions.

Methods

Qualitative Risk Analysis

We conducted a qualitative risk assessment of the effects of tidal power, climate change, and their interaction on ESA-listed species. We examined species-specific risks for potential effects by evaluating species exposure and sensitivity to each stressor. We examined exposure and sensitivity of their prey and predators to capture additional risk from food web interactions. We used expert opinion to determine the risk and uncertainty of tidal power development and climate change.

Assessments from a 2010 workshop on tidal power informed our categorization of environmental stressors and

Table 1. Aquatic animals occurring in or around Puget Sound that are federally protected under the *U.S. Endangered Species Act (ESA)*.

Taxon	Common name	Scientific name	ESA status	Functional group
Fish	Puget Sound Chinook salmon	*Oncorhynchus tshawytscha*	threatened	juvenile and adult wild salmon[a]
Fish	Hood Canal summer-run chum salmon	*Oncorhynchus keta*	threatened	juvenile and adult wild salmon[a]
Fish	Puget Sound steelhead trout	*Oncorhynchus mykiss*	threatened	juvenile and adult wild salmon[a]
Fish	coastal/Puget Sound bull trout	*Salvelinus confluentus*	threatened	none
Fish	southern DPS[b] Pacific eulachon (smelt)	*Thaleichthys pacificus*	threatened	forage fish[c]
Fish	southern DPS[b] green sturgeon	*Acipenser medirostris*	threatened	none
Fish	Puget Sound/Georgia Basin bocaccio	*Sebastes paucispinis*	endangered	juvenile and adult rockfish[d]
Fish	Puget Sound/Georgia Basin canary rockfish	*Sebastes pinniger*	threatened	juvenile and adult rockfish[d]
Fish	Puget Sound/Georgia Basin yelloweye rockfish	*Sebastes ruberrimus*	threatened	juvenile and adult rockfish[d]
Mammal	southern resident killer whale	*Orcinus orca*	endangered	southern resident killer whale
Mammal	north Pacific humpback whale	*Megaptera novaeangliae*	endangered	none
Mammal	eastern Steller sea lion	*Eumetopias jubatus*	threatened	sea lions[e]
Bird	Marbled Murrelet	*Brachyramphus marmoratus*	threatened	resident diving birds[f]

[a]*Chum populations not listed under the ESA are the largest fraction of functional group biomass.*
[b]*Distinct population segment.*
[c]*Eulachon is a very small fraction of functional group biomass.*
[d]*The 3 ESA-listed rockfish species are a small fraction of functional group biomass.*
[e]*Steller sea lions are 40% of functional group biomass.*
[f]*Marbled Murrelets are <1% of functional group biomass.*

assignment of individual risk effects and uncertainty (Polagye et al. 2011). Environmental stressors included the following effects: static (e.g., existence of the turbine, turbine foundation, and transmission cable); dynamic (e.g., blade strikes); chemical (e.g., acute or chronic release of toxic contaminants); acoustic (e.g., noise generation); electromagnetic field (e.g., from device or cables); and energy removal. A panel of experts assessed risk (exposure and level of effect) and uncertainty at 2 levels: pilot project (single device or small array installed for short duration for research and development) and large-scale commercial project (Polagye et al. 2011) (Supporting Information). We adapted assessments from the workshop to 5 risk categories and 3 uncertainty categories.

Locally relevant literature on the effects of climate change informed estimates of risks and uncertainty for ESA-listed species in the marine environment, their prey, and their predators in Puget Sound freshwater and marine environments (Snover et al. 2005; Battin et al. 2007; Mote et al. 2008; Cornell 2011). Climate-related stressors included changes in freshwater temperature, freshwater hydrology, sea level, ocean acidification, seawater salinity, seawater temperature, and rare storm events (Supporting Information). To explore effects on species from the interaction of tidal power and climate change, we identified 3 effects resulting from potential interactions: increasing hypoxic conditions from increased tempera-

ture (climate change) and tidal dampening (tidal power); temperature-related compromises to physiology increasing harm done by blade strikes; and counteracting effects of tidal muting and sea-level rise on tidal inundation (Supporting Information).

We converted qualitative risk scores to semiquantitative rankings by assigning numeric values ranging from 0 to 1 to each risk level (Table 2). We combined individual effect elements for tidal power and climate change and their uncertainty with geometric means to produce species-specific component risks of tidal power (pilot and commercial scales) and climate change (Supporting Information). Risk resulting from the interaction of tidal power and climate change started with a base of 0.1, and 0.2 was added for each potential interaction likely to negatively affect a given species.

To estimate total risk for each individual species (s), we combined risk scores for tidal power ($M_{p,s}$), climate change ($M_{c,s}$), and interaction ($M_{i,s}$) components by conceptualizing risk as a mortality hazard. If organisms must survive each component risk, total risk ($M_{t,s}$) is then

$$M_{t,s} = 1 - (1 - M_{p,s})(1 - M_{c,s})(1 - M_{i,s}). \qquad (1)$$

However, stressors on prey populations of a focal species may increase risk, whereas stressors on predators may decrease risk. To estimate changes to a focal species' risk resulting from such trophic interactions, we modified

Table 2. Risk and uncertainty scores used in qualitative analysis of the effects of climate change and tidal power development on *U.S. Endangered Species Act (ESA)*-listed species.[a]

Qualitative level of risk	Input risk values		Output risk bins	
	risk	uncertainty	risk	uncertainty
Low	0.1	0.01	≤ 0.2	≤ 0.01
Medium low	0.3		$0.2 < x \leq 0.4$	$0.01 < x \leq 0.05$
Medium	0.5	0.05	$0.4 < x \leq 0.6$	$0.05 < x \leq 0.1$
Medium high	0.7		$0.6 < x \leq 0.8$	$0.1 < x \leq 0.2$
High	0.9	0.1	> 0.8	> 0.2

[a]*Each stressor was given risk and uncertainty scores (input risk values), which were summarized with the geometric mean into output risk values. Output risk values were binned (output risk bins) for assignment of a qualitative level of risk.*

the risk of component factor x, tidal power (p), climate change (c), and their interaction (i) to incorporate risk to prey and predators:

$$W_{x,s} = [1 - (1 - M_{x,s})(1 - G(M_{x,f})]G(M_{x,g}), \qquad (2)$$

where $G(M_{x,f})$ and $G(M_{x,g})$ are the geometric means of species-specific risk to prey and predator species, respectively, and $M_{x,s}$ is the risk to the focal species. With these modifications to component risk scores, total risk incorporating trophic interactions ($W_{t,s}$) was calculated following Eq. 1:

$$W_{t,s} = 1 - (1 - W_{p,s})(1 - W_{c,s})(1 - W_{i,s}). \qquad (3)$$

We considered other calculation methods (e.g., simple averages of total risk), and total risk accumulation using this mortality hazard approach was not sensitive to the method we used. To avoid a false sense of precision, we recoded quantitative scores and their uncertainty back into qualitative rankings on a 5-point scale (Table 2).

Food Web and Blade-Strike Modeling

We used a mass-balanced, food web model of Puget Sound's central basin (Harvey et al. 2010; Harvey et al. 2012) built in Ecopath with Ecosim (EwE) software (Christensen & Walters 2004) to examine ESA-listed species' response to ecosystem effects of tidal power development and climate change. This Puget Sound central basin model includes 67 functional groups, which span nearly 5 trophic levels and contain from 1 to 100s of species, and 15 fishing fleets, each of which harvests a constant proportion of biomass of its target functional groups per year. The version of the Puget Sound EwE model we used differs from previous versions by the addition of a carrion functional group—dead biomass of large-bodied species. Some ESA-listed species in Puget Sound are represented by their own functional group in the model, whereas others are included in aggregate functional groups or excluded from the model (Table 1). For threatened and endangered species included in aggregate functional groups, we made the simplifying assumption that the population dynamics of the group represent those of the ESA-listed species. We used the food web

results only to evaluate the relative magnitude of change in the abundance of groups with ESA-listed species, and we caution against overinterpreting our results as quantitative and applicable to a specific species.

For tidal power scenarios, we focused on blade-strike mortality because data limitations prevented us from exploring scenarios on other tidal power–related stressors. We estimated mortality risk with a blade-strike model that likens blade strikes to random encounters between predators and prey (Wilson et al. 2007) (Supporting Information) and incorporates potential probabilities of avoidance (detection of turbines before an encounter) and evasion (eluding a blade strike during an encounter). We applied this model to those species whose depth distribution includes the range of proposed tidal power projects in Puget Sound (48–58 m) (Snohomish County Public Utility District 2011), assuming uniform species density throughout Puget Sound. We consider 3 scenarios for tidal power development: 2 turbines for 5 years (pilot project), 50 turbines for 50 years (moderate build-out), and 100 turbines for 50 years (commercial build-out) (Polagye et al. 2011).

We used details on 2 OpenHydro turbines considered for use by Snohomish County Public Utilities District to parameterize the blade-strike model (Snohomish County Public Utility District 2011; B. Polagye, personal communication) (Supporting Information). For copepods, euphausiids, jellyfish, and macrozooplankton, we assumed that lethality of strikes is independent of size and due to forces such as sheer stress and rapid pressure change (Dadswell & Rulifson 1994; Cada et al. 2006). Although sheer stress and pressure differentials are likely much lower than for hydropower turbines (Wilson et al. 2007; Amaral et al. 2011), the effects could be biologically meaningful to some small, delicate species. Lacking empirical or modeled estimates to parameterize this type of mortality, we applied 3 wide-ranging mortality probabilities for these groups: low, 0.02; moderate, 0.1; and high, 0.5.

For all other groups expected to encounter the turbines, we assumed the probability of mortality from blade strike increased with body size, reaching a plateau for the largest sized animals. We used 3 generalized mortality

curves with the following minimum and maximum, respectively, mortality probabilities: low, 0.002 and 0.02; moderate, 0.01 and 0.1; high, 0.05 and 0.5 (Supporting Information). These mortality curves span a wide range to reflect the paucity of data on the subject; moderate and high curves likely overestimate strike lethality (Normandeau Associates 2009; Amaral et al. 2011). To explore how the probability of fish avoiding turbine arrays affected our results, we used 3 avoidance probabilities for fish: 0.2, 0.5, and 0.9 (Normandeau Associates 2009; Amaral et al. 2011). Even though the limited evidence on strike mortality best supports the low mortality curve, we used the moderate mortality scenario in our sensitivity analyses so that mortality induced by the turbines was high enough to observe potential differences among avoidance or build-out scenarios. For the sensitivity analyses around avoidance and mortality probability, we used the commercial build-out scenario. We incorporated turbine-array-induced mortality in the EwE model as a fishery in which all harvest (i.e., mortality) resulting from blade strikes was allocated to the carrion group.

Climate-change scenarios affected the production of biomass in each functional group while still allowing trophic interactions to affect biomass. In these 50-year scenarios, we modeled different aspects of climate change, relying mostly on published scenarios developed for similar EwE modeling projects in this or other regions (Brown et al. 2009; Ainsworth et al. 2011; Busch et al. 2013) (Table 3 & Supporting Information). The scenarios focus on future changes in primary production, plankton community structure, seawater chemistry (dissolved oxygen, pH), and freshwater flooding. We imposed each climate-change scenario on the food web model individually at three strengths (conservative, moderate, and substantial) to test the sensitivity of the food web to each climate-change stressor and explore a range of magnitudes of climate-change impacts. We also imposed all climate-change stressors on the food web model together, adding their changes in productivity to define the forcing function of the combined scenario (Ainsworth et al. 2011). We developed combined scenarios at all three strengths, separating positive and negative changes in primary productivity.

We modeled simultaneous effects of climate change and tidal power development by applying each of the combined climate-change scenarios with the commercial tidal power scenario. This approach implies an additive interaction between the 2 factors. However, it allows trophic effects to mediate the nature of the interaction.

From the food web model output, we calculated percent change, relative to the baseline model, in the number of individuals in ESA-listed functional groups (or functional groups that contain ESA-listed species or act as proxies for them), converting biomass to individuals

with the average mass per individual of the functional group. We also determined which functional groups experienced the largest increases (90–100th percentile; referred to as top decile) and decreases (0–10th percentile; referred to as bottom decile) in biomass relative to the baseline model. We based calculations on year 50 of each simulation.

Results

Qualitative Risk Analysis

The qualitative risks from tidal energy development and climate change varied considerably, but some general patterns emerged. For most species, risk and uncertainty scores for tidal power development were greater under commercial-scale build-out than for the pilot project (Fig. 1). This pattern was stronger when food web effects were incorporated than when only focal species were assessed. Risk scores for tidal power development were generally greater than risk scores for climate change. Uncertainty scores for climate change were similar to those of tidal power development at the pilot-project scale but less than tidal power development with commercial build-out. When tidal power development and climate change were considered together, total risk and uncertainty ranged from medium-low to high under the pilot-project scenario and from medium-low to very high under the commercial build-out scenario, depending on whether the assessment incorporated food web interactions. When food web effects were taken into account, all species exhibited high uncertainty and high or very high total risk for pilot and commercial build-out scenarios, respectively.

Several patterns in risk scores were shared by ESA-listed species with similar ecology under scenarios of both climate change and tidal power development. Under the pilot build-out scenario, focal species assessments indicated juvenile chum (*Oncorhynchus keta*) and Chinook salmon (*Oncorhynchus tshawytscha*) and bull trout (*Salvelinus confluentus*) were the most at risk from climate-change effects. These 3 species inhabit cold, freshwater tributaries or estuaries during their early ontogeny. Under the commercial build-out scenario, marine mammals and birds were the least at risk from tidal power development. Incorporating food web effects for these species resulted in elevated risk and uncertainty scores from tidal power development, primarily due to effects on their prey species (e.g., salmonids and forage fish).

The greatest risk posed by tidal power development was from dynamic effects of turbines (i.e., blade strikes), particularly under commercial build-out scenarios (Supporting Information). The greatest risks posed by climate change were changes in freshwater temperatures and hydrology and rare climatic events, particularly for salmonids. The only other high-risk score was for the

Table 3. Percent change[a] in productivity of select functional groups for each climate-change scenario imposed on the food web model.

	Scenario strength			
	conservative	*moderate*	*substantial*	*Reference*
Freshwater environment	−2	−4	−8	this article
Ocean acidification	−5	−15	−25	Busch et al. 2013
Plankton community structure	variable	variable	variable	Ainsworth et al. 2011
Ocean deoxygenation				Ainsworth et al. 2011
small	−4	−7	−11	
medium	−11	−22	−33	
large	−18	−37	−55	
Primary production				Ainsworth et al. 2011; Brown et al. 2009
positive	−10	−20	−40	
negative	10	20	40	

[a]*Change is imposed in a linear manner. Values of change are for the end of the 50-year scenario (see Supporting Information for details).*
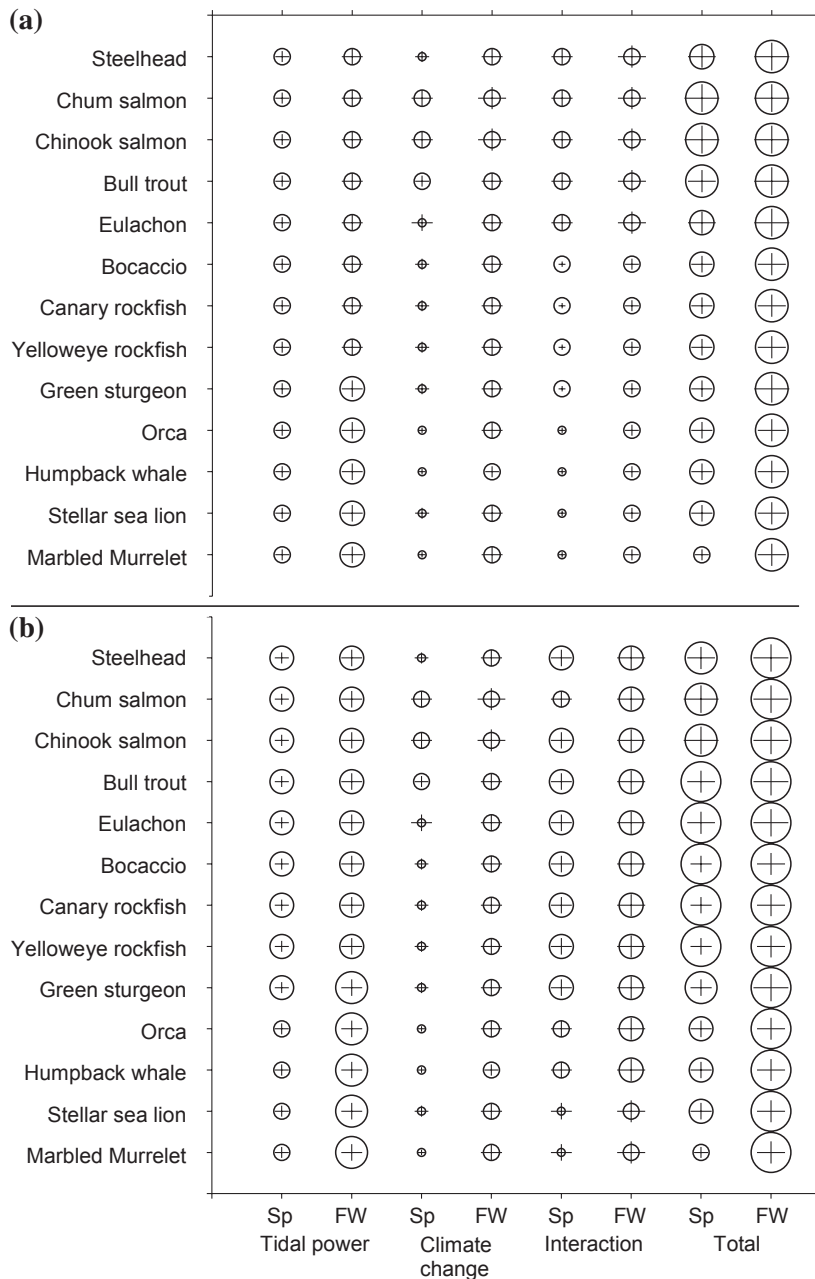

Figure 1. Qualitative estimates of risk of the effects of tidal power development, climate change, their interaction, and total risk on U.S. Endangered Species Act (ESA)-listed species derived from assessments of species-specific (Sp) risks and risks that incorporated food web (FW) interactions for (a) pilot project with 2 turbines and (b) commercial-scale project. Small to large circles equate with very low to very high risk, respectively (5 risk categories), and small to large crosses equate with low to high uncertainty (3 categories). Scales of risk and uncertainty are not necessarily equivalent.

effects of ocean acidification on macrozooplankton prey (Supporting Information). Overall risk and uncertainty scores from tidal power development or climate change for prey and predators were similar to that of ESA-listed species (Supporting Information), especially at the commercial-scale build-out.

Food Web and Blade-Strike Models

Among vertebrates, the number of individuals struck per year was low for most functional groups but highest for juvenile herring (*Clupea pallasii*), ratfish (*Hydrolagus colliei*), Pacific hake (*Merluccius productus*), and forage fish under the commercial build-out scenario (Table 4). Under all build-out scenarios, <1% of individuals in each functional group was struck. Juvenile rockfish, Pacific hake, and jellyfish had the largest percentages of their population struck per year (>0.09%). Abundance of groups with ESA-listed species did not change in response to any tidal power development scenario or sensitivity-analysis scenario applied to the EwE model (Fig. 2).

Functional groups responded variably to different aspects of climate change (Supporting Information); deoxygenation and primary-production scenarios had the largest effects on the food web. For brevity, we discuss only the results of scenarios when all aspects of climate change were applied together (combined scenarios) (Fig. 2). When the primary-production forcing was negative, the combined scenarios led to a decrease in the abundance of functional groups with ESA-listed species. In general, the magnitude of this effect was less than expected from the individual climate-change scenarios for all groups expect salmonids, suggesting some mitigation when all aspects of climate change are considered together. Biomass declines were largest for salmonids, forage fish, euphausiids, and macrozooplankton under the negative primary-productivity forcing scenarios; octopus, suspension feeders, microzooplankton, and some primary producers experienced the largest biomass increases. When primary-production forcing was positive, the combined climate-change scenarios had mixed effects on groups with ESA-listed species. Abundance of wild salmon decreased; abundance of rockfish, sea lions, and resident diving birds increased; and the direction of change in abundance of forage fish varied with scenario strength. The magnitude of these effects could not be predicted by summing the results of scenarios on the individual aspects of climate change. The most responsive groups in these scenarios were similar to those that had the largest changes in biomass in response to the scenarios with decreased primary production.

Adding the blade-strike scenarios to the combined climate-change scenarios caused changes in abundance of groups with ESA-listed species and biomass of all func-tional groups that were basically identical to the changes caused by the climate-change scenarios alone (Fig. 2 & Supporting Information).

Discussion

Our findings suggest that incorporating climate change into assessments of biological effects of hydrokinetic energy projects is warranted. In fact, failure to recognize the potential effects of climate change could lead to natural resource managers having unrealistic expectations for future abundance of many species. Results of qualitative analyses indicated that both tidal power development and climate change pose risks for ESA-listed species in Puget Sound and that risk was greatest when climate change and tidal power development were considered together. Risk assignments increased when consideration of potential effects went beyond single species to incorporate elements of the food web, indicating the importance of an ecosystem approach. Although food web modeling suggested no detectable change in abundance of groups with ESA-listed species in response to tidal power development, it indicated that abundance would be strongly affected by climate change. Natural resource managers often must consult on competing uses of the marine environment under great uncertainty. Our tiered risk-analysis approach builds on assessment techniques developed for guiding such management decisions and is appropriate for consultation concerning other types of marine technologies.

Effects of Tidal Energy

In the qualitative analysis, blade strikes created the most risk from tidal power development for ESA-listed species. However, the blade-strike model, as parameterized for OpenHydro tidal power turbines, suggested relatively few blade strikes on groups with ESA-listed species but that blade strikes could be a management concern for some species under commercial-scale tidal power development. In the absence of field data, it is difficult to know which result is more accurate. Any strikes will likely constitute "take," as described in the ESA, and would, therefore, merit additional Section 7 consultations. The results of the blade-strike model depended greatly on data inputs for encounter rates, and predictions would likely change if parameterized for other tidal power turbines. As with modeling of wind-turbine effects (Chamberlain et al. 2006), our assumptions about the probability of avoidance had a large effect on the number of blade strikes, suggesting the need for field studies to assess the ability of species to avoid turbines. Empirical data are also needed on strike lethality. For example, behavioral interactions between species (e.g., predator avoidance) may affect strike mortality (e.g., lethal strikes with high-speed

Table 4. Annual strikes by tidal power turbines for different functional groups, including those with species listed under the *U.S. Endangered Species Act (ESA)*, under 3 build-out scenarios (pilot, moderate, and commercial) and, for the commercial scenario only, under 3 scenarios for the ability of organisms to avoid strikes (avoidance).

Functional group	ESA-listed species	Population struck (%)					Number of individuals struck				
		pilot	moderate	commercial avoidance			pilot	moderate	commercial avoidance		
				low	moderate	bigb			low	moderate	bigb
Southern resident killer whales	X	0.00	0.01	0.03	0.03	0.03	0	0	0	0	0
Sea lions	X	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Harbor seals		0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Juvenile wild salmon	X	0.00	0.00	0.00	0.00	0.00	0	16	50	32	6
Adult wild salmon	X	0.00	0.00	0.00	0.00	0.00	0	4	12	8	2
Juvenile hatchery salmon		0.00	0.00	0.00	0.00	0.00	0	1	5	3	1
Adult hatchery salmon		0.00	0.00	0.00	0.00	0.00	0	0	1	0	0
Juvenile pink salmon		0.00	0.00	0.00	0.00	0.00	0	1	4	3	1
Adult pink salmon		0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Juvenile herring		0.00	0.01	0.05	0.02	0.01	514	18,726	76,177	37,451	9,522
Adult herring		0.00	0.01	0.02	0.01	0.00	30	1,097	3,510	2,193	439
Forage fish	X	0.00	0.00	0.00	0.00	0.00	108	3,932	12,772	7,864	1,597
Spiny dogfish		0.00	0.01	0.02	0.02	0.00	6	208	665	415	83
Ratfish		0.00	0.03	0.09	0.06	0.01	510	18,477	59,139	36,954	7,392
Pacific hake		0.00	0.06	0.17	0.12	0.02	132	4,798	13,085	9,597	1,636
Juvenile rockfish	X	0.00	0.06	0.17	0.11	0.02	48	1,759	5,565	3,518	696
Adult rockfish	X	0.00	0.01	0.02	0.02	0.00	1	25	70	49	9
Squid		0.00	0.01	0.03	0.02	0.00	36	1,293	4,085	2,587	511
Copepods[a]		0.00	0.00	0.00	0.00	0.00	31,536,000	31,536,000	31,536,000	31,536,000	31,536,000
Euphausiids[a]		0.00	0.00	0.00	0.00	0.00	15,506,725	31,536,000	31,536,000	31,536,000	31,536,000
Jellyfish		0.00	0.04	0.08	0.09	0.08	439	15,991	29,219	31,982	29,219
Macrozoops[a]		0.00	0.03	0.03	0.03	0.03	1,004,168	31,536,000	31,536,000	31,536,000	31,536,000

[a]*Number of individuals struck does not change among all scenarios because, when necessary, we fixed the probability that these species would encounter the turbine array to 1 to prevent it from exceeding 1. When this probability is fixed to 1, the model outputs that individuals in these species groups are struck by turbines every second of the day, every day of the year.*
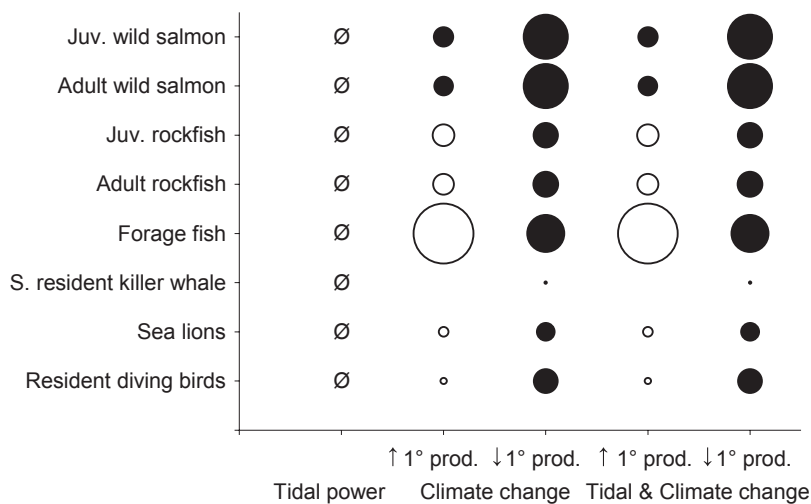
Figure 2. Percent change in the abundance of U.S. Endangered Species Act (ESA)-listed species (or their proxies) in response to the scenario of commercial build-out of tidal power, moderate scenario of climate change with increases or decreases in primary productivity (prod.), and the interaction of these scenarios (Ø, zero change in abundance for a given scenario; blank space, change in abundance for a scenario <2%; juv., juvenile; S., southern; white circles, increase in abundance; black circles, decrease in abundance; circle size positively correlates with the magnitude of abundance change).

travel). If encountering turbines without strike is traumatic enough to damage larval fish, the implications of turbine arrays for ESA-listed populations in Puget Sound may be greater than expected from this analysis. Finally, accurate estimates of species vulnerability to turbine arrays depend on spatially explicit species density data. Marine species tend to aggregate to forage at the interface of differing energetic environments (e.g., tidal rips) and rest in low-current areas. We suggest reparameterization of the blade-strike model if and when such data become available.

Interactions among marine species and operating tidal power infrastructure are currently poorly understood and will likely be highly complex. For example, some fish highly sensitive to vibrations or electromagnetic fields may respond more negatively to array operations than expected, and invasive and other species may colonize benthic structure associated with the turbines and change the local benthic community (Boehlert & Gill 2010). By extracting energy from marine waters, commercial-scale tidal power arrays could alter the physical structure of ecosystems by changing tidal height, currents, and wave energy (Polagye et al. 2011), potentially affecting biological processes such as larval dispersal. Until more data on tidal power projects are collected, one must necessarily rely on expert opinion and ecological theory to generate a preliminary understanding of the effects of tidal power development on marine communities.

Effects of Climate Change

Results of both the qualitative-risk and food web model analyses suggest that climate change could have large effects on Puget Sound's ESA-listed species and marine food web. These results emphasize the importance of considering shifts in the environmental baseline when considering the effects of actions on ESA-listed species.

Because of the uncertainty inherent in our understanding of the effects of climate change, the most useful results for natural resource managers to consider are the broad patterns of how ESA-listed species and the food web responded to climate change. Similar to results for the California Current System (Ainsworth et al. 2011), we found that the effects of climate change varied among species in their strength and direction. Some species (e.g., octopus, suspension feeders) increased biomass in response to the climate-change scenarios. This outcome captures the concept that some species will benefit from changes to their physical environment and ecological community.

Experts scored the effects of climate change as less than the effects of tidal power development but assigned more uncertainty to tidal power development than to climate change. Additional research is needed to assess the role of uncertainty in risk-score assignment in this context. For example, the substantial knowledge base on how freshwater processes affect salmonid populations could cause experts to assign more risk to this potential stressor than other climate-change stressors. Other factors could also contribute to differential risk assessment between climate change and tidal power development in both the qualitative analysis (e.g., scoring was done by different groups of experts) and the food web analysis (e.g., multispecies functional groups may not reflect dynamics of the ESA-listed species and data limitations prevented inclusion of many stressors).

Our results emphasize the importance of considering all aspects of climate change simultaneously. Effects of individual aspects of climate change (e.g., ocean acidification) can be different than cumulative effects of many aspects of climate change. Combining all aspects of climate change in a single scenario mitigated their effects on the food web under some scenarios but magnified them in others. This mixed reaction to the combined scenarios was not found by Ainsworth et al. (2011) and

may be due to data limitations that caused us to model change in primary production differently and exclude range-shift scenarios. We were able to incorporate few climate-change effects in our scenarios. In particular, no climate-change scenario directly affected productivity of marine mammals or birds. These groups have large trophic effects on many fish species via predation, and predation mortality strongly affected abundance of those species, such as forage fish and salmon, with relatively short life cycles whose productivity was affected greatly by the climate-change scenarios.

Importance of an Ecosystem Approach

The risk to ESA-listed species from tidal power development and climate change was particularly prevalent when we considered trophic interactions (Fig. 1). This suggests that failing to consider trophic interactions may cause resource managers to underestimate the risk of any individual action. Information on how human activities could alter the food web as a whole may lead to a better understanding of their consequences, especially under changing environmental conditions. Examining groups that have large biomass changes in response to climate change and tidal power development scenarios can yield insights into if and how marine ecosystems could change and whether human activities that affect the ecosystem may require modification. For example, species declines in response to climate change and other actions may suggest a need for modification of harvest rates or species protection (Kaplan et al. 2010).

The food web model we used to consider ecosystem-level effects of climate change and tidal power development was an imperfect tool for doing so. It is not spatially explicit and does not incorporate physical data, so it could not incorporate spatial variance in climate-change effects. It does not incorporate likely alterations in species' ranges under climate change, and migratory species were affected by climate change scenarios only for the fraction of the year that they existed in the model domain. We did not account for climate-change effects on migratory species outside the model domain. For this reason, we considered our results a conservative estimate of how migratory species in the model and those species trophically linked to them will respond to climate change. Our scenarios of climate change and tidal power are best considered methodological demonstrations for how to scale consideration of effects from single species to an entire food web. Spatially and temporally explicit ecosystem models and climate-change-forced projections for relevant environmental variables are needed to properly capture future risk, especially in locales where human use of the environment coincides with a high density of ESA-listed species.

Incorporating Climate Change into ESA Section 7 Consultations

Our results are most appropriate for examining relative effects, rather than for evaluating them quantitatively. There is great uncertainty about how hydrokinetic energy development and climate change may affect marine environments and species and a reliance on expert opinion due to a lack of data (Polagye et al. 2011). Quasi-quantitative approaches based on expert opinion can provide a false sense of predictability (Good et al. 2003) and be susceptible to bias (McCarthy et al. 2004), but they can be useful when done in a rigorous way that accounts for uncertainty. We found high uncertainty surrounding the total risk from climate change and tidal power for most ESA-listed species, especially when trophic interactions were considered. Some uncertainty could be reduced by targeted data collection and development of better models. Differences in results between the food web modeling approach and more standard qualitative risk analysis indicates that the 2 approaches may capture different aspects of risk to ESA-listed species and the community as a whole. This suggests that there is value in incorporating the thinking represented by both approaches into Section 7 consultations and other evaluations of marine energy projects, especially in data-poor situations.

By simultaneously considering how climate-change and hydrokinetic-energy projects may affect both ESA-listed species and their food web, natural resource managers can evaluate the consequences of burgeoning alternative-energy development in the context of changes due to another large stressor on marine ecosystems. Furthermore, simultaneous consideration will allow natural resource managers to assess if the effects of energy development could be detectable against a background of climate change. Our findings suggest that the effects of climate change on marine ecosystems may be so large that they could overwhelm the effects of some other actions. This result suggests that failing to consider the effects of climate change along with other known stressors on the marine environment could impair our understanding of how society's actions will affect species and communities.

A central question raised by this exercise is how to evaluate the effect of new technologies on species and communities. Technological advances are leading to new options for transportation, construction, and energy generation and transmission. Balancing the known benefits of these technologies against uncertain, potential harm to species and ecosystems is a challenge forced to the forefront by the ESA. A dilemma raised by renewable-energy projects is that they may do direct harm to species but also prevent further emissions from the burning of fossil fuels, the cause of both climate change and ocean acidification. A relevant question for policy makers and ethicists

is whether certain, direct harm to species in a localized area caused by human actions like renewable-energy generation is justified if these actions slow the progression of global environmental change and its effects on all species and ecosystems. In this context, adaptive management during early implementation of new technologies make detection of and protection from environmental harm more likely and allows for data collection on heretofore unknown environmental effects.

Acknowledgments

Supporting Information

Qualitative risk and uncertainty scores (Appendices S1–S4), description of the blade-strike model and its parameterization (Appendices S5–S6), description of the climate-change scenarios and their application to functional groups (Appendix S7–S8), and response of functional groups to scenarios (Appendix S9–S12) are available as part of the online article. The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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