

1 APPENDIX MS2013-04. APPLICATION OF THE NORTHERN CALIFORNIA CURRENT  
2 ECOTRAN MODEL TO PELAGIC ECOSYSTEM SCENARIOS FOR THE 2013 CALIFORNIA  
3 CURRENT INTEGRATED ECOSYSTEM ASSESSMENT

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7 SUMMARY

8 An end-to-end ecosystem model of the Northern California Current (NCC ECOTRAN)  
9 is used to investigate the scale of effects that the observed variability within the plankton,  
10 jellyfish, and forage fish community have upon higher trophic levels and upon fishery  
11 production. Ocean survey observations of the plankton and pelagic fish community made  
12 over the 1998 - 2007 period allow for basic inferences of inter-annual differences in food  
13 web structure. Study of the wide range of ocean and biological conditions over this decade-  
14 long period can improve our model extrapolations and strengthen our confidence in  
15 predicted ecosystem responses to long-term climate change. The simple scenarios  
16 developed here alter only a few key lower- and mid-trophic level groups, but they  
17 demonstrate that changes in community composition and trophic structure can have  
18 effects upon higher trophic levels and fisheries as important as variability in primary  
19 production levels. Thus, consideration of changes in trophic relationships, that can result  
20 both from long-term changes in local climate and inter-regional changes in migration  
21 patterns population distributions, are as necessary as the study of the impact of climate  
22 change upon individual species.

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24 INTRODUCTION AND GOALS

25 Understanding the effects of climate variability and climate change is a key  
26 challenge for marine resource managers on the US West Coast and for the Integrated  
27 Ecosystem Assessment. Hollowed *et al.* (2013) identify eight foci needed to improve the  
28 projections of climate impacts on fish, fisheries, and fishery-dependent communities.  
29 Among these is improved understanding of the mechanisms underlying fish and shellfish  
30 responses to environmental drivers. These authors argue that observations and  
31 understanding of the present-day responses of prey groups, such as zooplankton and  
32 forage fish, to changes in ocean condition are needed to predict future responses to climate  
33 change.

34 For the Oregon and Washington continental shelf, a relatively rich data set of  
35 plankton, forage fish, and primary production is available in summer months (e.g., Brodeur  
36 *et al.*, 2005; Emmett *et al.*, 2006; and sources cited below). Below, I combined these data  
37 sets within the framework of an end-to-end trophic network model, the NCC ECOTRAN  
38 ecosystem model, to ask: How does inter-annual variability in food web structure affect  
39 specific groups and fisheries production? The NCC ECOTRAN model is used to estimate  
40 ecosystem-level and functional group responses to observed inter-annual changes over the  
41 past decade in phytoplankton production and biomass, copepod community composition  
42 and biomass, the biomass of large jellyfishes, and changes in the forage fish community.  
43 These scenarios provide a baseline measure of current inter-annual variability and point to  
44 considerations necessary to design scenarios predicting responses to future climate  
45 change.

46 Punt and colleagues (2013) discuss the simulation testing of fishery management  
47 strategies for climate change. Given the uncertainties related to precisely forecasting  
48 species responses to climate, these authors argue for a more general consideration of how  
49 the ecological system may change in the future, and whether management strategies are  
50 robust to this change. The work below illustrates recent inter-annual shifts in the food web,  
51 and can inform how climate-driven shifts in productivity may alter fisheries in the future.

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53 MODEL STRUCTURE AND SCENARIO METHODOLOGY

54 The “NCC ECOTRAN” end-to-end ecosystem model describes the trophic  
55 interactions between 83 functional groups and 17 separate fisheries and gear types in the  
56 benthic and pelagic environments of the Northern California Current upwelling system  
57 (Steele & Ruzicka, 2011; Ruzicka *et al.*, 2012). The model domain covers the Oregon and  
58 Washington continental shelf ecosystem during the summer seasons (June -  
59 September). Here, ten alternate configurations of the model are developed, one  
60 representative of the food web structure for each year 1998 through 2007.

61 At its heart, the NCC ECOTRAN model is a map of the flow of energy through the  
62 entire food web from lower trophic-level producers to upper trophic-level consumers and  
63 fisheries. As an “end-to-end” model, it accounts for nutrient input via upwelling, includes  
64 nutrient recycling via bacterial metabolism of detritus, and can account for advective losses  
65 of plankton production. The production of each functional group within the trophic  
66 network may be driven by nutrient or plankton production input at the base of the food  
67 web — as from a plankton production model or an upwelling index time-series. The  
68 distribution of all energy consumed by each group to metabolism, to production, to each  
69 predator and fishery group, and to detritus as feces or unconsumed production is taken

70 into account. The response of upper trophic levels to changes to plankton dynamics,  
71 community variability or other energy flow rearrangements, or to physiological changes  
72 can readily be estimated. Further, in this configuration the propagation of parameter  
73 uncertainty (including diet uncertainty) through the model is accounted for (Ruzicka *et al.*,  
74 2011; Fig. 1).

75 Production of biological groups for a particular year, as estimated by NCC ECOTRAN,  
76 is the creation of new biomass – the sum of recruitment of juveniles and growth in body  
77 size during that year. In the long term, changes in production, after accounting for  
78 mortality, will lead to concomitant changes in stock size and biomass. However, on an  
79 annual scale, changes in production may not lead to substantial, immediate changes in  
80 stock size or biomass, particularly for long-lived species. For instance, a baleen whale  
81 population with a biomass production rate of only 4% yr<sup>-1</sup> will not crash if that production  
82 rate is halved for a single year. However, the focus on production in NCC ECOTRAN is  
83 particularly relevant for considering climate effects, which we can envision as long term  
84 extensions of production rates that will ultimately impact stock size and biomass.

85 Similarly, NCC ECOTRAN focuses on annual fishery production, which is the product  
86 of biomass production of targeted species and a fishing mortality rate. It is akin to  
87 removing a fixed fraction of ‘surplus production’; it differs from removing fixed fractions of  
88 (standing stock) biomass. Over decadal scales associated with climate change, however,  
89 harvests of fixed fractions of biomass will lead to catches that track long term changes in  
90 biomass production rates.

91 The NCC ECOTRAN model complements other California Current ecosystem models  
92 in two areas: 1) Assessing the role of small pelagic fishes, including sardine, anchovy,  
93 herring, and juvenile salmon, and 2) providing Monte Carlo simulations to address  
94 observational uncertainties and natural variability in scenario simulations. This model has  
95 proven useful for examining scenarios of alternative (forage fish, krill, jellyfish) food web  
96 pathways (Ruzicka *et al.*, 2012).

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98 DATA SOURCES

99 The NCC ECOTRAN model incorporates benthic and pelagic survey data to infer the  
100 network of trophic interactions during the productive upwelling season. Survey data  
101 include: 1) Bonneville Power Administration-sponsored pelagic fish and zooplankton  
102 surveys of the Oregon and Washington shelf (Brodeur *et al.*, 2005; Morgan *et al.*, 2005;  
103 Emmett *et al.*, 2006), and 2) the NWFSC and AFSC west coast groundfish surveys (e.g.,  
104 Keller *et al.*, 2008). Phytoplankton biomass and production rates (1998 - 2007) were  
105 estimated from SeaWIFS satellite Chl a data (A. Thomas, U. Maine) and the Eppley version

106 of the Vertically Generalized Production Model (M. Behrenfeld, Oregon State University;  
 107 [www.science.oregonstate.edu/ocean.productivity/standard.product.php](http://www.science.oregonstate.edu/ocean.productivity/standard.product.php)). Fishery data  
 108 were obtained from the Pacific States Marine Fisheries Commission data servers: PacFIN  
 109 ([pacfin.psmfc.org](http://pacfin.psmfc.org)) and RecFIN ([recfin.org](http://recfin.org)). Diet information was obtained from the  
 110 literature of local NCC studies. Physiological rate definitions were obtained from the global  
 111 literature.

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 113 SCENARIO DESIGN

114 A series of model scenarios, representing individual years from 1998-2007, was  
 115 produced to explore inter-annual differences in food web configuration and the short-term  
 116 impact upon higher trophic levels. This set of years includes both unproductive (e.g. El  
 117 Niño) years and years in which primary producers, zooplankton, and forage fish were in  
 118 high abundance. Each scenario estimates changes to energy flow throughout the food web  
 119 necessary to accommodate, and as consequence of, observed changes among nine  
 120 manipulated lower- and mid-trophic level groups: phytoplankton, copepods, large  
 121 carnivorous jellyfishes (*Chrysaora fuscescens*), and the major forage fish groups (sardine,  
 122 anchovy, herring, and smelt). In each scenario, the total grazing or predation pressure on a  
 123 given producer group was not changed, rather a scenario was created by changing the  
 124 biomass and consumption of each manipulated group at the direct expense of any and all  
 125 competitor groups. Similarly, transfer efficiencies were held constant, implying no change  
 126 to physiology (assimilation efficiencies, growth efficiencies, and weight-specific production  
 127 rates) nor to predation vulnerabilities.

128 Individual scenarios were constructed as deviations from the baseline model  
 129 representing the mean Northern California Current food web structure inferred from ocean  
 130 observations made across the 1998 - 2007 upwelling seasons (April - September). Inter-  
 131 annual biomass anomalies are shown in Table 1. For each scenario year, these factors were  
 132 applied to the baseline biomasses of nine manipulated groups (Table 1, top). Each scenario  
 133 also altered the phytoplankton primary production rate, thus scenario results represent  
 134 both structural changes to the trophic network and changes to the overall productivity of  
 135 the ecosystem as a whole. Consequences of each scenario are expressed as changes in the  
 136 production rate ( $t\ km^{-2}\ y^{-1}$ ) of each functional group relative to the inter-annual mean, or  
 137 'base', model.

138 Table 1 illustrates the range of biological and oceanographic conditions experienced  
 139 on the Northern California Current continental shelf during 1998-2007, which result from  
 140 both local and basin-scale processes. Years in which biomass was low among the  
 141 manipulated groups include both an El Niño year, 1998, and a year of delayed seasonal

142 transition to upwelling conditions, 2005. The delayed spring-transition to local upwelling  
 143 conditions had negative impacts on many species (Peterson *et al.*, 2006). In other years,  
 144 such as 2003, biomasses of some mid-trophic level groups (e.g., forage fish) was high, while  
 145 other lower trophic-level groups were slightly less abundant than the decadal mean. In  
 146 2002, the northern region of the California Current ecosystem supported higher-than-  
 147 average biomasses of most of the manipulated groups, despite being in a slight positive  
 148 (unproductive) phase of the basin-scale PDO. Local Northern California Current conditions  
 149 in 2002 may have been influenced primarily by an influx of cold, nutrient-rich fresh water  
 150 from the north, with the result of higher-than-average phytoplankton production and  
 151 biomass (Venrick *et al.*, 2003). Applying anomalies from the decadal mean biomasses of  
 152 low- and mid- trophic level groups as scenario scaling factors simulates the effects of inter-  
 153 annual variability in the pelagic community structure on the upper food web and fisheries.

154 To account for uncertainty in scenarios, I have adapted the principles of the  
 155 “ECOSENSE” simplified Bayesian Synthesis methodology developed by Aydin *et al.* (2007).  
 156 The uncertainties associated with each group’s biomass, diet, and physiology were defined  
 157 *a priori* from observation or from a pre-established parameter “pedigree” of poorly known  
 158 parameters. A series of parameter sets were randomly drawn via Monte Carlo sampling  
 159 from each parameter’s distribution. From among many thousands of potential models, only  
 160 parameter sets that produced systems within thermodynamic balance were retained.  
 161 Scenario manipulations applied consistently across this set of potential ‘base’ models  
 162 express the range of potential system responses within the limits of the defined parameter  
 163 uncertainties and parameter-set retention criteria (Ruzicka *et al.*, 2013).

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## 165 RESULTS

166 For each scenario year, I show the relative change in production of several  
 167 important pelagic groups (Table 2, Fig. 2) and fisheries (Table 3, Fig. 3) relative to the  
 168 decadal mean baseline model. The years 1998 (an El Niño year) and 2001 were generally  
 169 bad years across multiple groups and trophic levels (Table 2). Years 2002, 2003, and 2006  
 170 were generally good years for most groups. At the base of the food web, variation in total  
 171 phytoplankton production and the biomass of the small phytoplankton was comparatively  
 172 small while variability among jellyfish and forage fishes was large (Table 1).

173 *Patterns of interannual variability:* Generally, there is correspondence between  
 174 years of high phytoplankton biomass and production rates up the food web. This is largely  
 175 driven by the extreme years of the time-series: the low production El Niño year of 1998  
 176 and the high phytoplankton production years of 2002, 2006, and 2007. For instance, in

177 1998 many fish groups' production declined by 10-50%, and seabird production declined  
178 by >50%. In 2002 and 2006, many fish groups increased in production by 20-50%.

179 Aside from these extreme years, the response of the trophic groups and fisheries  
180 depended not on mean abundance of the groups manipulated in the scenarios but on  
181 abundance of particular lower trophic level groups, and trophic interactions. For instance,  
182 1999 had below-average abundances for every manipulated group, but a mix of above- and  
183 below-average production for other groups. The complexity of observed patterns across  
184 years show that competitive trophic interactions, direct and indirect, can have as great an  
185 impact on the production of higher trophic level groups as variability in production at the  
186 base of the food web. In particular, forced imposition of jellyfish and forage fish variability  
187 within the scenarios drives strong responses within the network of trophic relationships.  
188 First, forage fishes are both prey to higher trophic levels and competitors for lower trophic  
189 level production. When forage fish biomass is high (2000-2003) or low (1998-1999, 2006),  
190 salmon, seabirds, and marine mammal predators respond similarly. Groups that compete  
191 with forage fishes (squid, planktivorous rockfishes) respond in the opposite manner.  
192 Second, jellyfishes, particularly sea nettles (*Chrysaora fuscescens*), can become a major  
193 consumer of plankton production off the Oregon and Washington coasts in some years  
194 (Ruzicka *et al.*, 2007). Model scenarios show juvenile fishes and young salmon are less  
195 productive during years of especially high jellyfish abundance (2001, 2007). Fisheries,  
196 however, appeared insensitive to jellyfish variability - yet these scenarios do not consider  
197 the effect of jellyfish on recruitment of juvenile fishes to the fisheries in subsequent years.

198 As noted above, the two "across-the-board" poorest years were 1998 and 2001. In  
199 1998, scenario drivers were nearly all in alignment for forcing poor production throughout  
200 the whole food web. Both plankton production and forage fish biomasses were  
201 anomalously low, thus production through the system was low. In 2001, however,  
202 phytoplankton production was low while copepod, jellyfish, and forage fish abundances  
203 were high. The example of 2001 shows how variability of mid-trophic level energy  
204 pathways have large affects upon the rest of the food web. In these scenarios, abundant  
205 forage fish and jellyfish use a higher proportion of plankton production at the direct  
206 expense of other planktivores (e.g. production of euphausiids, juvenile fishes, small squid  
207 decline by 25-60%). Groups such as rockfishes, flatfishes, hake, and Pacific mackerel that  
208 rely more heavily upon these "alternate" planktivores than upon the forage fishes decline  
209 by 20-60%. For groups that prey directly upon forage fishes (salmon, seabirds, marine  
210 mammals), the 2001 scenario was near base model conditions.

211 Fishery/gear types responded in the same manner as their target groups. The  
212 behavior of the different fishery/gear types to food web variability (i.e., the nine  
213 manipulated groups) can be divided into two main types. Pelagic fishery/gear types that  
214 target forage fishes (seine, gill nets, non-trawl pelagic net gear) or that target salmon,

215 Pacific mackerel, jack mackerel, and tuna (recreational fishers, seine, gill nets, troll gear,  
216 offshore hook & line gear) performed best during the forced high forage fish years (2000-  
217 2003), and production increased by as much as four-fold during these years. Gear types  
218 that targeted hake and sablefish (mid-water trawls, non-shrimp bottom trawls, fish pots)  
219 performed best during years of higher euphausiid production (2006-2007), with roughly  
220 30-50% increases in production during these years. Note that the reported increases in  
221 production do not imply an equivalent increase in harvest for that year, but would lead to  
222 large increases in biomass and harvest over longer time periods.

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224 DISCUSSION

225 *Predicting sensitivity to future ocean variability:* This simple scenario modeling  
226 exercise shows the short-term effects of observed community changes within the plankton  
227 and forage fish community upon higher trophic levels and upon production of fished  
228 species. Primary production and food web structural variability over the past decade  
229 suggests that pelagic fishery production generally varied within 50% - 200% about the  
230 decadal mean. Variability was higher among fisheries that target forage species. Energy  
231 flow (fish production) to the major fishery species within the Northern California Current  
232 ecosystem, Pacific hake (largely harvested using mid-water trawl gear), has varied from  
233 40% below to 50% above the decadal mean (Table 3). Hake were not a forced group in  
234 these scenarios; these simulations represent the net effect of observed variability in  
235 primary production and trophic network structure.

236 A single year of low biomass production will not lead to immediate sharp declines in  
237 fisheries catch, but these declines will occur if such unproductive conditions are persistent  
238 under future climate scenarios. We cannot at present predict what future levels of  
239 productivity will be under climate change. However, the period from 1998-2007 provides a  
240 range of annual production rates that could be used in the future to bracket what may  
241 occur under climate change.

242 In the context of climate change impacts on the California Current, the results here  
243 illustrate the impacts of local conditions and the importance of understanding the trophic  
244 structure and linkages within the food web. Though considerable effort has gone into  
245 modeling climate at the scale of the North Pacific (Overland & Wang 2007), and basin-scale  
246 patterns such as the PDO are known to influence productivity in the California Current  
247 (Checkley & Barth 2009), the modeling effort here suggests that local patterns can also  
248 have profound effects on biomass and fishery productivity. For instance, the timing of  
249 upwelling off Oregon and Washington in 2005 and intrusion of cold, northerly water in  
250 2002 may have set the stage for the observed changes in lower trophic levels and the

251 modeled responses of the food web. Downscaled oceanographic models that can include  
252 climate change and capture these local processes will be needed to improve climate change  
253 forecasts for marine populations (Hollowed *et al.*, 2013).

254 Except during years of extremes in lower-trophic level productivity, an  
255 understanding of the variability in the network of trophic connections is essential to  
256 predicting responses of higher trophic levels. There may not be a close correlation between  
257 plankton production and the production of particular higher trophic level species (at least  
258 on an inter-annual scale). Instead, energy flow through the food web is modified by the  
259 composition of the mid-trophic level community, leading to varied responses of higher  
260 trophic level groups. Additionally, within the Northern California Current, mid-trophic level  
261 composition is very much modified by migration of the more abundant species (e.g., hake  
262 and sardine) and the very poorly understood factors that control production of jellyfish  
263 populations. As climate change is expected to cause both changes to local plankton  
264 production, i.e., to local upwelling (Bakun, 1990) and to region-scale migration patterns  
265 and population distributions (Ainsworth *et al.*, 2011; Pinsky & Fogarty, 2012), we can  
266 logically expect even larger variability in fishery production in the future. Model scenarios  
267 can be crafted to show fishery sensitivities to defined future changes in local production  
268 and shifts in population distributions.

269 *Euphausiids: a fundamental limitation in our understanding of the Northern*  
270 *California Current ecosystem:* Euphausiids are dominant prey species for many of the most  
271 abundant fishes (Miller *et al.*, 2010) and are an influential energy transfer node in the  
272 Northern California Current ecosystem. In these scenarios, squid, rockfishes, Pacific  
273 mackerel, and Pacific hake covary with euphausiid abundance; 2006 and 2007 being years  
274 of especially high abundance, 2000, 2001, and 2004 being years of low abundance. Forage  
275 fishes and euphausiids are assumed to be competitors for plankton production and covary  
276 inversely. Thus, squid, rockfishes, Pacific mackerel, and Pacific hake also covary inversely  
277 with forage fish. Because synoptic time-series observations of euphausiid abundance along  
278 the Oregon and Washington coasts are not available, I could not force scenarios with  
279 observed euphausiid biomasses. Patterns of euphausiid variability are, and must remain, a  
280 construct of the model based on our assumptions of competition for plankton production  
281 and euphausiid responses to large-scale oceanographic processes.

282 From a single-species perspective, several authors have investigated optimal fishery  
283 management strategies for coping with variable climate (MacCall, 2002; King & Mcfarlane,  
284 2006; A'mar *et al.*, 2009; Haltuch *et al.*, 2011). As shown by the NCC ECOTRAN work  
285 presented here, climate and interannual variability in productivity drive strong responses  
286 throughout the food web and fisheries. If climate change leads to altered trends or  
287 variability in both productivity and community composition in the California Current, we

288 are challenged to move beyond single-species approaches to develop management  
289 strategies that are robust at the level of the whole food web.

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Table 1. Base model conditions (top row) and individual, annual anomalies used as scaling factors in scenario analyses (individual year / base). Base model conditions are the mean plankton and forage fish biomasses ( $\text{t km}^{-2}$ ) observed over the 1998 - 2010 period (April - September) and the mean phytoplankton production rate ( $\text{t km}^{-2} \text{ y}^{-1}$ ) over the 1998 - 2007 period (April - September) as estimated from satellite data. Red shading indicates a large ( $\geq 20\%$ ) reduction relative to base model conditions, green shading indicates a large ( $\geq 20\%$ ) increase over base model conditions.

|   | phytoplankton      |                    |                | copepods <sup>2</sup> |               | jellyfish      | forage fishes   |               |               |               |
|---|--------------------|--------------------|----------------|-----------------------|---------------|----------------|-----------------|---------------|---------------|---------------|
|   | production rate    | small <sup>1</sup> | large          | small <sup>3</sup>    | Large         | sea nettle     | sardine         | anchovy       | herring       | smelt         |
| <b>base biomass (<math>\text{t km}^{-2}</math>)</b> | 7853.1 $\pm$ 948.7 | 4.7 $\pm$ 0.2      | 33.6 $\pm$ 8.9 | 8.3 $\pm$ 1.4         | 2.8 $\pm$ 1.5 | 7.9 $\pm$ 12.8 | 15.2 $\pm$ 18.0 | 4.3 $\pm$ 6.5 | 2.6 $\pm$ 3.4 | 1.8 $\pm$ 2.6 |
| <b>1998</b>   | 0.87               | 0.95               | 0.75           | 0.27                  | 2.25          | --             | 0.21            | 0.01          | 0.59          | 0.02          |
| <b>1999</b>   | 0.86               | 0.98               | 0.86           | 0.74                  | 0.47          | 0.04           | 0.34            | 0.004         | 0.15          | 0.002         |
| <b>2000</b>   | 0.89               | 0.98               | 0.89           | 1.60                  | 1.43          | 0.01           | 1.63            | 0.27          | 3.93          | 5.20          |
| <b>2001</b>   | 0.91               | 0.98               | 0.84           | 1.35                  | 0.42          | 3.99           | 2.17            | 0.58          | 3.28          | 3.93          |
| <b>2002</b>   | 1.16               | 1.07               | 1.31           | 1.44                  | 0.99          | 1.21           | 0.85            | 3.26          | 1.20          | 0.37          |
| <b>2003</b>   | 1.07               | 0.99               | 0.93           | 0.95                  | 0.71          | 0.30           | 4.17            | 0.93          | 1.69          | 0.46          |
| <b>2004</b>   | 0.98               | 0.96               | 0.77           | 1.47                  | 1.20          | 0.21           | 0.37            | 4.85          | 0.31          | 0.77          |
| <b>2005</b>   | 0.99               | 0.96               | 0.87           | 0.33                  | 0.54          | 0.77           | 0.54            | 1.05          | 0.15          | 0.15          |
| <b>2006</b>   | 1.08               | 1.05               | 1.25           | 1.08                  | 0.72          | 0.29           | 0.31            | 0.13          | 0.20          | 0.10          |
| <b>2007</b>   | 1.19               | 1.08               | 1.52           | 1.05                  | 0.67          | 5.12           | 0.89            | 0.13          | 0.27          | 0.17          |

<sup>1</sup>Small phytoplankton are  $< 10\mu\text{m}$

<sup>2</sup>The base model was built on zooplankton data from BPA cruise vertical net data while copepod scenarios were scaled based on time-series observations off the central Oregon coast (NH-Line station NH05, 9km from coast, data from W. Peterson NWFSC).

<sup>3</sup>Small copepods are  $< 0.025 \text{ mg C}$

Table 2: Interannual scenarios: effect of variability among bottom- and mid-trophic level groups (phytoplankton, copepods, jellyfish, forage fish) on the production of a few select groups. Values are ratios of scenario to base model production rates. Scenarios created by scaling base model biomasses of selected groups by observed biomass anomalies (Table 1). Red shading indicates  $\geq 20\%$  reduction and green shading indicates  $\geq 20\%$  increase over base model. Error terms represent 1 standard deviation of scenarios applied to 445 random, balanced model configurations. (see Fig. 2)

|                              | 1998        | 1999        | 2000        | 2001        | 2002        | 2003        | 2004        | 2005        | 2006        | 2007        |
|------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| <b>Planktivores</b>          |             |             |             |             |             |             |             |             |             |             |
| E. pacifica                  | 0.88 ± 0.06 | 0.96 ± 0.03 | 0.78 ± 0.06 | 0.76 ± 0.04 | 1.14 ± 0.06 | 0.95 ± 0.01 | 0.71 ± 0.04 | 1.05 ± 0.06 | 1.24 ± 0.02 | 1.41 ± 0.06 |
| juvenile fish                | 0.78 ± 0.11 | 1.09 ± 0.08 | 0.87 ± 0.10 | 0.42 ± 0.11 | 1.24 ± 0.08 | 0.91 ± 0.06 | 0.92 ± 0.10 | 0.84 ± 0.10 | 1.57 ± 0.09 | 0.74 ± 0.20 |
| small squid                  | 0.98 ± 0.07 | 1.29 ± 0.10 | 0.80 ± 0.08 | 0.41 ± 0.08 | 1.09 ± 0.07 | 0.78 ± 0.13 | 0.81 ± 0.10 | 1.11 ± 0.07 | 1.65 ± 0.10 | 0.95 ± 0.21 |
| <b>juvenile salmon</b>       |             |             |             |             |             |             |             |             |             |             |
| coho yearling                | 0.79 ± 0.06 | 1.17 ± 0.09 | 1.03 ± 0.09 | 0.36 ± 0.08 | 1.32 ± 0.05 | 0.86 ± 0.08 | 1.09 ± 0.07 | 0.91 ± 0.06 | 1.62 ± 0.09 | 0.61 ± 0.14 |
| Chinook yearling             | 0.81 ± 0.06 | 1.17 ± 0.08 | 1.01 ± 0.09 | 0.38 ± 0.08 | 1.29 ± 0.05 | 0.86 ± 0.07 | 1.05 ± 0.07 | 0.92 ± 0.06 | 1.61 ± 0.08 | 0.66 ± 0.13 |
| Chin. subyearling            | 0.82 ± 0.05 | 1.18 ± 0.08 | 0.99 ± 0.08 | 0.39 ± 0.07 | 1.29 ± 0.05 | 0.84 ± 0.07 | 1.05 ± 0.06 | 0.95 ± 0.06 | 1.60 ± 0.08 | 0.68 ± 0.12 |
| <b>piscivorous fishes</b>    |             |             |             |             |             |             |             |             |             |             |
| coho salmon                  | 0.54 ± 0.08 | 0.70 ± 0.10 | 1.35 ± 0.13 | 0.86 ± 0.12 | 1.42 ± 0.14 | 1.76 ± 0.40 | 1.07 ± 0.20 | 0.80 ± 0.07 | 0.93 ± 0.12 | 0.86 ± 0.10 |
| Chinook salmon               | 0.52 ± 0.09 | 0.62 ± 0.10 | 1.37 ± 0.15 | 0.91 ± 0.11 | 1.44 ± 0.16 | 1.76 ± 0.40 | 1.06 ± 0.22 | 0.77 ± 0.07 | 0.84 ± 0.12 | 0.92 ± 0.11 |
| Pacific mackerel             | 0.97 ± 0.08 | 1.16 ± 0.06 | 0.83 ± 0.08 | 0.54 ± 0.05 | 1.07 ± 0.07 | 0.76 ± 0.15 | 0.70 ± 0.09 | 1.06 ± 0.07 | 1.52 ± 0.07 | 1.26 ± 0.11 |
| Pacific hake                 | 0.99 ± 0.08 | 1.17 ± 0.08 | 0.83 ± 0.07 | 0.59 ± 0.05 | 1.06 ± 0.07 | 0.79 ± 0.15 | 0.69 ± 0.08 | 1.09 ± 0.07 | 1.50 ± 0.08 | 1.34 ± 0.07 |
| <b>Rockfishes</b>            |             |             |             |             |             |             |             |             |             |             |
| planktivores <sup>4</sup>    | 1.07 ± 0.07 | 1.37 ± 0.09 | 0.69 ± 0.07 | 0.40 ± 0.05 | 1.03 ± 0.07 | 0.63 ± 0.11 | 0.70 ± 0.09 | 1.13 ± 0.06 | 1.77 ± 0.10 | 1.17 ± 0.13 |
| piscivores <sup>5</sup>      | 0.78 ± 0.10 | 0.93 ± 0.10 | 1.05 ± 0.11 | 0.72 ± 0.09 | 1.23 ± 0.10 | 1.23 ± 0.30 | 0.86 ± 0.13 | 0.96 ± 0.07 | 1.21 ± 0.12 | 1.10 ± 0.12 |
| benthivores <sup>6</sup>     | 0.95 ± 0.06 | 1.24 ± 0.08 | 0.82 ± 0.08 | 0.48 ± 0.06 | 1.13 ± 0.06 | 0.77 ± 0.09 | 0.77 ± 0.07 | 1.03 ± 0.06 | 1.65 ± 0.10 | 1.12 ± 0.11 |
| <b>flatfishes</b>            |             |             |             |             |             |             |             |             |             |             |
| pelagic feeders <sup>7</sup> | 0.69 ± 0.10 | 0.84 ± 0.11 | 1.15 ± 0.13 | 0.78 ± 0.10 | 1.28 ± 0.12 | 1.41 ± 0.35 | 0.90 ± 0.17 | 0.89 ± 0.08 | 1.12 ± 0.13 | 1.08 ± 0.09 |
| benthic feeders <sup>8</sup> | 0.80 ± 0.05 | 0.99 ± 0.06 | 0.99 ± 0.07 | 0.64 ± 0.09 | 1.25 ± 0.04 | 0.88 ± 0.04 | 0.83 ± 0.05 | 0.88 ± 0.04 | 1.41 ± 0.08 | 1.17 ± 0.14 |
| <b>seabirds and mammals</b>  |             |             |             |             |             |             |             |             |             |             |
| sooty shearwaters            | 0.40 ± 0.09 | 0.53 ± 0.13 | 1.51 ± 0.21 | 0.96 ± 0.15 | 1.54 ± 0.24 | 2.04 ± 0.55 | 1.20 ± 0.35 | 0.72 ± 0.08 | 0.72 ± 0.15 | 0.73 ± 0.15 |
| common murre                 | 0.45 ± 0.10 | 0.59 ± 0.13 | 1.44 ± 0.18 | 0.93 ± 0.15 | 1.47 ± 0.22 | 1.98 ± 0.51 | 1.11 ± 0.31 | 0.74 ± 0.08 | 0.79 ± 0.15 | 0.79 ± 0.14 |
| small odontocetes            | 0.60 ± 0.11 | 0.69 ± 0.14 | 1.19 ± 0.16 | 0.98 ± 0.16 | 1.38 ± 0.15 | 1.55 ± 0.41 | 0.93 ± 0.20 | 0.81 ± 0.08 | 0.94 ± 0.16 | 1.22 ± 0.23 |
| large pinnipeds              | 0.73 ± 0.07 | 0.88 ± 0.08 | 1.12 ± 0.10 | 0.76 ± 0.08 | 1.27 ± 0.10 | 1.32 ± 0.24 | 0.90 ± 0.12 | 0.91 ± 0.06 | 1.16 ± 0.09 | 1.09 ± 0.08 |

<sup>4</sup> planktivorous rockfishes include: bank, blue, darkblotched, greenstriped, redstripe, rosy, sharpchin, splitnose, shortbelly, widow, Pacific ocean perch

<sup>5</sup> piscivorous rockfishes include: black, bocaccio, canary, chillipepper, yelloweye, yellowtail

<sup>6</sup> benthivorous rockfishes include: cabezon, China, quillback, rosethorn, rougheye, shortraker, shortspine and longspine thornyhead

<sup>7</sup> pelagic-feeding flatfishes: Pacific halibut, arrowtooth flounder, petrale sole

<sup>8</sup> benthic feeding flatfishes: English sole, Dover sole, rex sole

Table 3: Results of inter-annual scenarios: estimated effects on pelagic fishery and major bottom-fish fishery production rates. Values are the ratio of the annual scenario to base model production rates. Scenarios were created by scaling base model biomasses of select bottom- and mid-trophic level groups (phytoplankton, copepods, jellyfish, and forage fish) by the observed biomass anomalies of each year (Table 1). Scenarios assume constant effort across years. Red shading indicates  $\geq 20\%$  reduction and green shading indicates  $\geq 20\%$  increase over base model. Error terms represent 1 standard deviation of scenarios applied to 445 random, thermodynamically balanced model configurations. (see Fig. 3).

|                             | 1998        | 1999        | 2000        | 2001        | 2002        | 2003        | 2004        | 2005        | 2006        | 2007        |
|-----------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| longline                    | 0.93 ± 0.07 | 1.12 ± 0.07 | 0.89 ± 0.07 | 0.61 ± 0.05 | 1.09 ± 0.07 | 0.90 ± 0.14 | 0.72 ± 0.08 | 1.05 ± 0.06 | 1.44 ± 0.08 | 1.28 ± 0.07 |
| troll gear                  | 0.45 ± 0.06 | 0.56 ± 0.07 | 1.47 ± 0.17 | 0.94 ± 0.12 | 1.52 ± 0.22 | 1.89 ± 0.45 | 1.17 ± 0.32 | 0.74 ± 0.06 | 0.77 ± 0.08 | 0.81 ± 0.12 |
| hook-line inshore           | 0.92 ± 0.07 | 1.11 ± 0.07 | 0.88 ± 0.07 | 0.63 ± 0.05 | 1.08 ± 0.07 | 0.99 ± 0.14 | 0.69 ± 0.07 | 1.05 ± 0.06 | 1.43 ± 0.07 | 1.29 ± 0.07 |
| hook-line offshore          | 0.72 ± 0.06 | 0.88 ± 0.06 | 1.16 ± 0.10 | 0.75 ± 0.07 | 1.26 ± 0.11 | 1.32 ± 0.23 | 0.90 ± 0.14 | 0.91 ± 0.06 | 1.15 ± 0.07 | 1.08 ± 0.08 |
| pelagic net gear            | 0.27 ± 0.04 | 0.43 ± 0.03 | 1.39 ± 0.08 | 1.28 ± 0.10 | 1.04 ± 0.05 | 3.56 ± 0.21 | 0.39 ± 0.06 | 0.58 ± 0.03 | 0.55 ± 0.05 | 1.10 ± 0.07 |
| gill nets                   | 0.56 ± 0.04 | 0.58 ± 0.06 | 1.93 ± 0.16 | 1.14 0.12   | 1.36 ± 0.07 | 1.56 ± 0.17 | 0.80 ± 0.10 | 0.62 ± 0.05 | 0.79 ± 0.07 | 0.72 ± 0.06 |
| seine                       | 0.21 ± 0.01 | 0.38 ± 0.02 | 1.37 ± 0.09 | 1.34 0.10   | 1.00 ± 0.04 | 3.89 ± 0.08 | 0.34 ± 0.03 | 0.55 ± 0.02 | 0.47 ± 0.02 | 1.12 ± 0.07 |
| recreational <sup>9</sup>   | 0.61 ± 0.05 | 0.75 ± 0.06 | 1.26 ± 0.10 | 0.83 0.08   | 1.37 ± 0.09 | 1.58 ± 0.20 | 1.01 ± 0.13 | 0.84 ± 0.05 | 1.00 ± 0.07 | 0.95 ± 0.07 |
| mid-water trawls            | 0.98 ± 0.08 | 1.17 ± 0.08 | 0.83 ± 0.07 | 0.59 ± 0.05 | 1.06 ± 0.07 | 0.80 ± 0.15 | 0.69 ± 0.08 | 1.09 ± 0.07 | 1.49 ± 0.08 | 1.33 ± 0.07 |
| bottom trawls <sup>10</sup> | 0.91 ± 0.07 | 1.09 ± 0.07 | 0.91 ± 0.07 | 0.63 ± 0.05 | 1.12 ± 0.07 | 0.94 ± 0.15 | 0.75 ± 0.08 | 1.04 ± 0.06 | 1.41 ± 0.08 | 1.26 ± 0.07 |
| fish pots                   | 0.93 ± 0.07 | 1.12 ± 0.07 | 0.89 ± 0.07 | 0.61 ± 0.05 | 1.09 ± 0.07 | 0.90 ± 0.14 | 0.72 ± 0.08 | 1.05 ± 0.06 | 1.44 ± 0.07 | 1.28 ± 0.07 |

<sup>9</sup> all gear types and platform (boat vs. shore-based) combined

<sup>10</sup> excluding shrimp trawls

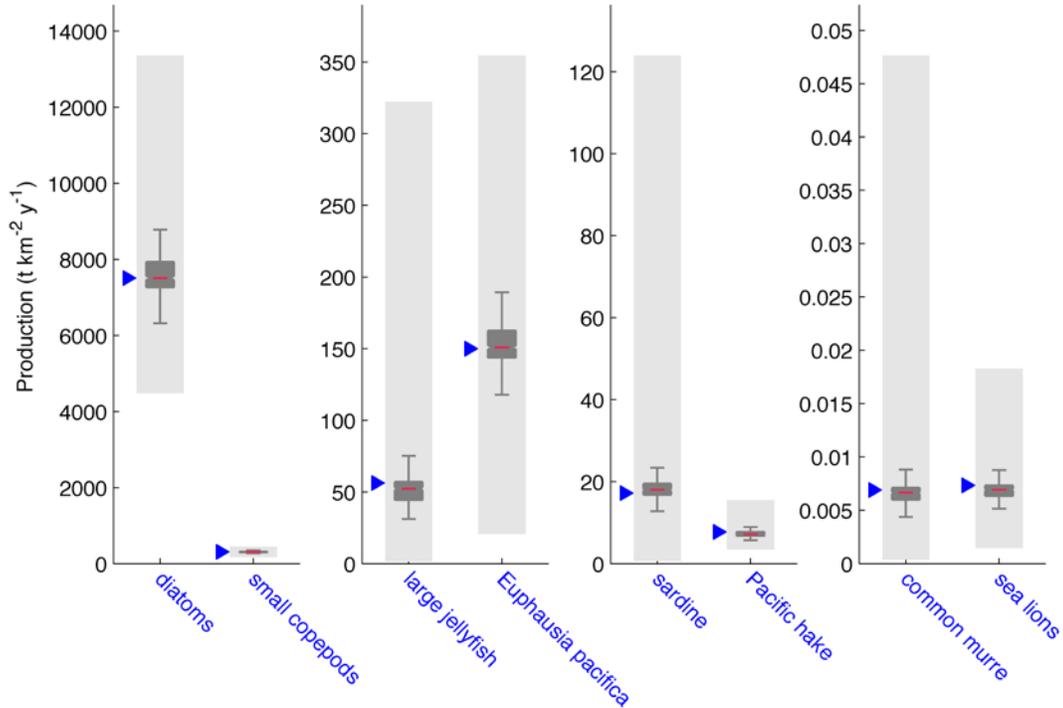


Figure 1. Production rate distributions of Monte Carlo iterations about the decadal mean, baseline model, showing a few example functional groups. Parameter sets were randomly generated by sampling within the 1 CV range of mean parameter values (biomass, production/biomass ratio, growth efficiency, assimilation efficiency, and diet preference). Gray shading shows sampling space of production rates (product of biomass and production/biomass ratio) as defined by observed inter-annual variability (or as defined by assumed parameter 'pedigrees' for poorly observed groups such as the euphausiids). Box plots show distribution of 445 thermodynamically balanced models. Blue arrows indicate the value of the defining 'type' base model.

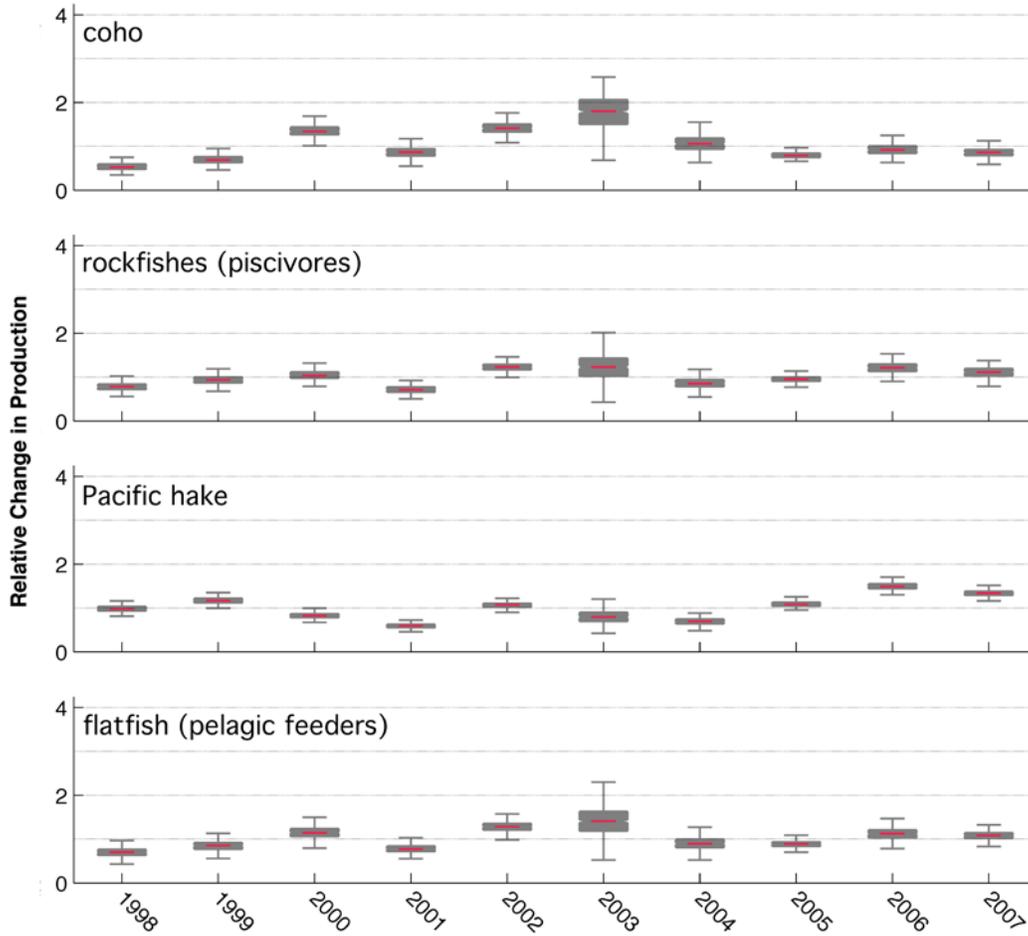


Figure 2. Scenarios showing effects of interannual variability among bottom- and mid-trophic level groups (phytoplankton, copepods, jellyfish, and forage fish) upon the production rates of select fish groups. Boxplots show distributions of changes in production rates relative to the inter-annual mean (ratio of scenario production rate to inter-annual mean, or 'base' model production rate). Boxplots show distributions of scenarios applied to 445 random, thermodynamically balanced model parameter configurations. A value of 1 on the y-axis represents no change from the inter-annual mean. (see Table 2)

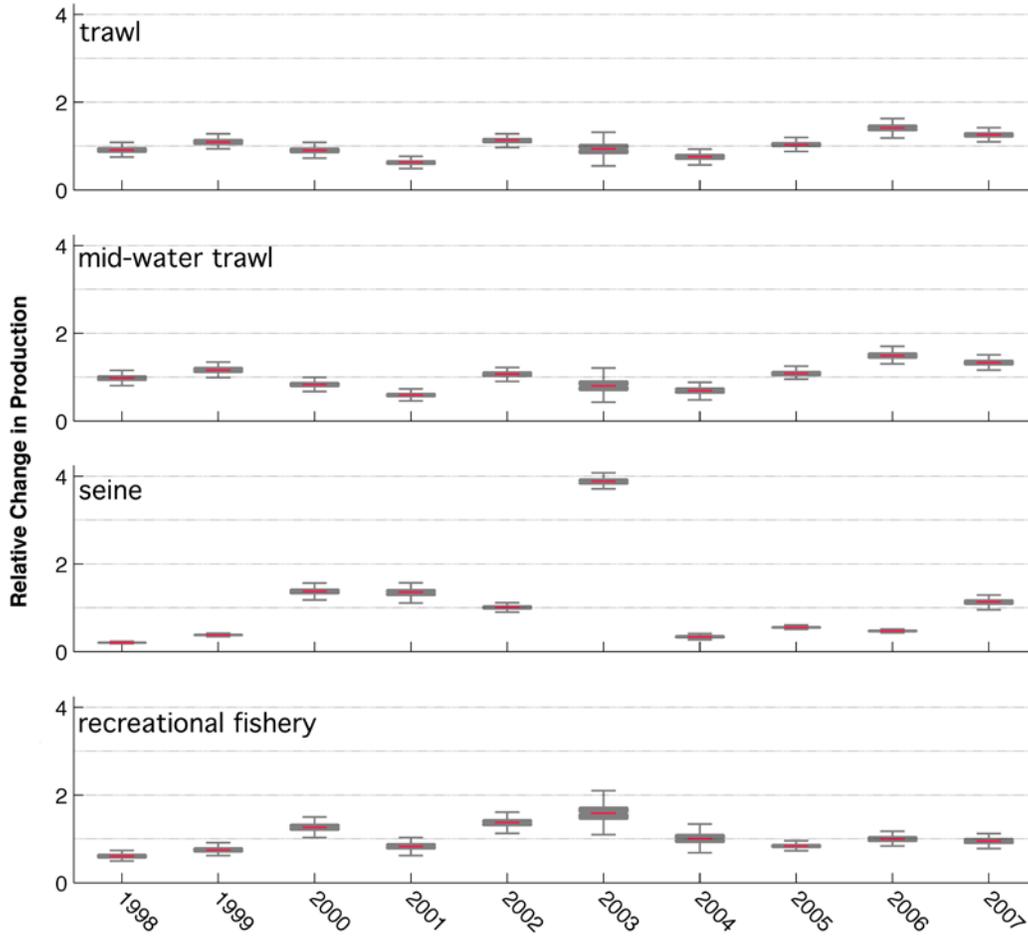


Figure 3. Scenarios showing effects of interannual variability among bottom- and mid-trophic level groups (phytoplankton, copepods, jellyfish, and forage fish) upon the production rates of select pelagic fishery groups. Boxplots show distributions of changes in production rates relative to the inter-annual mean (ratio of scenario production rate to inter-annual mean, or 'base' model production rate). Boxplots show distributions of scenarios applied to 445 random, thermodynamically balanced model parameter configurations. A value of 1 on the y-axis represents no change from the inter-annual mean. (see Table 3)