

Ziegler, J. P., Gregory-Eaves, I. and Solomon, C. T. 2017. Refuge increases food chain length: modeled impacts of littoral structure in lake food webs. – *Oikos* doi: 10.1111/oik.03517

Appendix 1

Section 1. Implicitly modeling refuge

To determine if our results were robust to an alternative method of modeling refuge we enhanced refuge implicitly by increased the scaling parameter (x), which allowed us to model refuge via a Holling type III functional response (Fig. A1). A type III functional response is applicable when the consumption of prey by a predator declines at a given threshold of prey density (Hassell et al. 1977). Therefore, predator encounter rates and consumption will decline when prey numbers are reduced to the point where only well-hidden or inaccessible prey items remain in refuge. There is empirical evidence for a transition from a type II functional response to a type III functional response when describing consumption of resources with increased habitat structure in our context (Kaiser 1983, Folsom and Collins 1984, Lipcius and Hines 1986, Anderson 2001). Our results of increased food chain length with increase refuge were consistent even when refuge was modeled implicitly (Fig. A2).

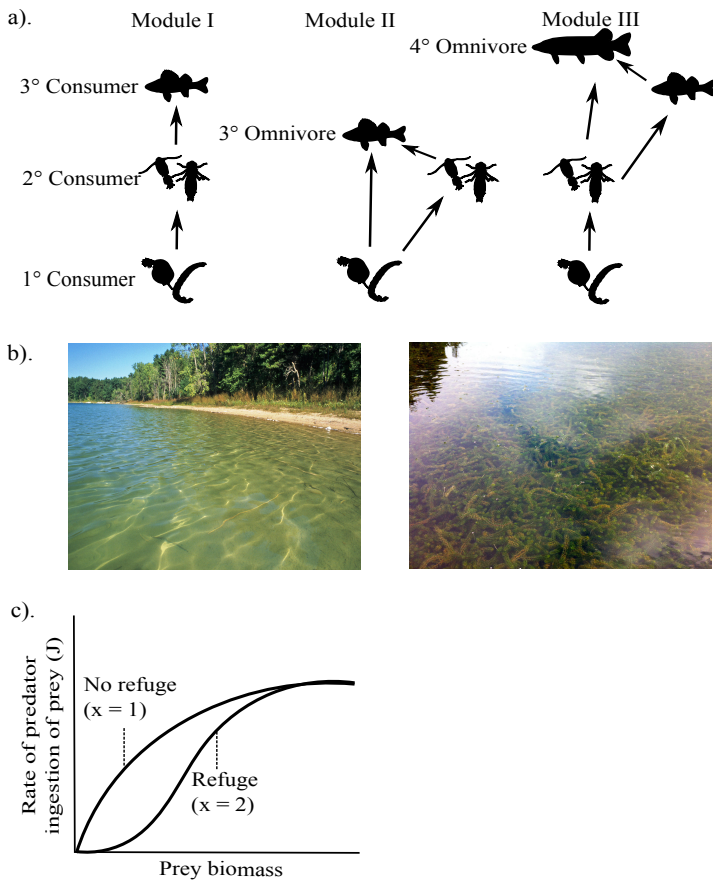


Figure A1. Food web modules and modeled effects of habitat structure on refuge. (a) three food web module structures used to simulate shallow lake food webs. Arrows denote biomass flows between consumers. (b) comparison of a lake with no littoral habitat structure (left) to high littoral habitat structure (right) in the form of macrophytes. (c) predator ingestion rates, J , are governed by a functional response, which is affected by the presence of refuge. Specifically, as refuge increases (e.g. panel b left to right) ingestion rates follow a Holling type III functional response as x approaches 2. At lower prey biomasses attack rates by predators decrease as these prey items are within structural refuge.

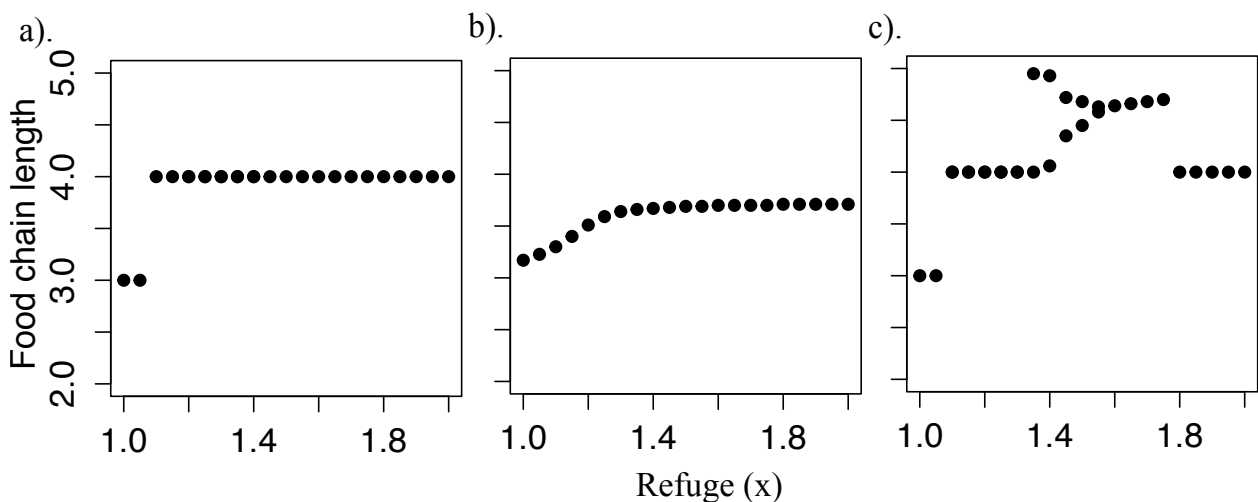


Figure A2. Implicitly modeled refuge effects on food chain length (FCL). Results are plotted for food web modules: (a) I, (b) II and (c) III. Implicitly modeling refuge provided similar results to that of explicitly modeling refuge (Fig. 3).

Section 2. Sensitivity analyses

We used local sensitivity analyses to explore the robustness of the food chain length (FCL) results presented in our manuscript to changes in all model parameters. We first increased and decreased all parameters by 10, 20 and 50 percent while holding all others at their baseline value to illustrate each parameter's ability to increase FCL from its baseline conditions (Fig. A3). We then increased the transition rate to and from vulnerable prey classes (m , our metric of refuge) by 10 percent and determined if any parameters had the ability to increase FCL from its baseline conditions (in this case $m = 0.1$ and $r = 1$ were the baseline values for these parameters) (Fig. A4). Lastly, we increased productivity (r , our metric of refuge) by 10 percent and determined if any parameters had the ability to increase FCL from its baseline conditions (in this case $m = 0$ and $r = 1.1$ were the baseline values for these parameters) (Fig. A5). Substantial increases and decreases in model parameters, for the most part, did not lead to increased FCL (Fig. A3–A5). When FCL increases were observed with parameter changes, the increases were always smaller than those caused by a change in m (our metric of refuge). Our results of increased FCL with increased m and little change in FCL with increased r were robust to substantial model parameter changes (Fig. A4, A5). We note that the parameter p defines food web module I and II, therefore, we did not consider it in our sensitivity analyses. We set $m = 0$ for all decreases in m because the baseline value of $m = 0$.

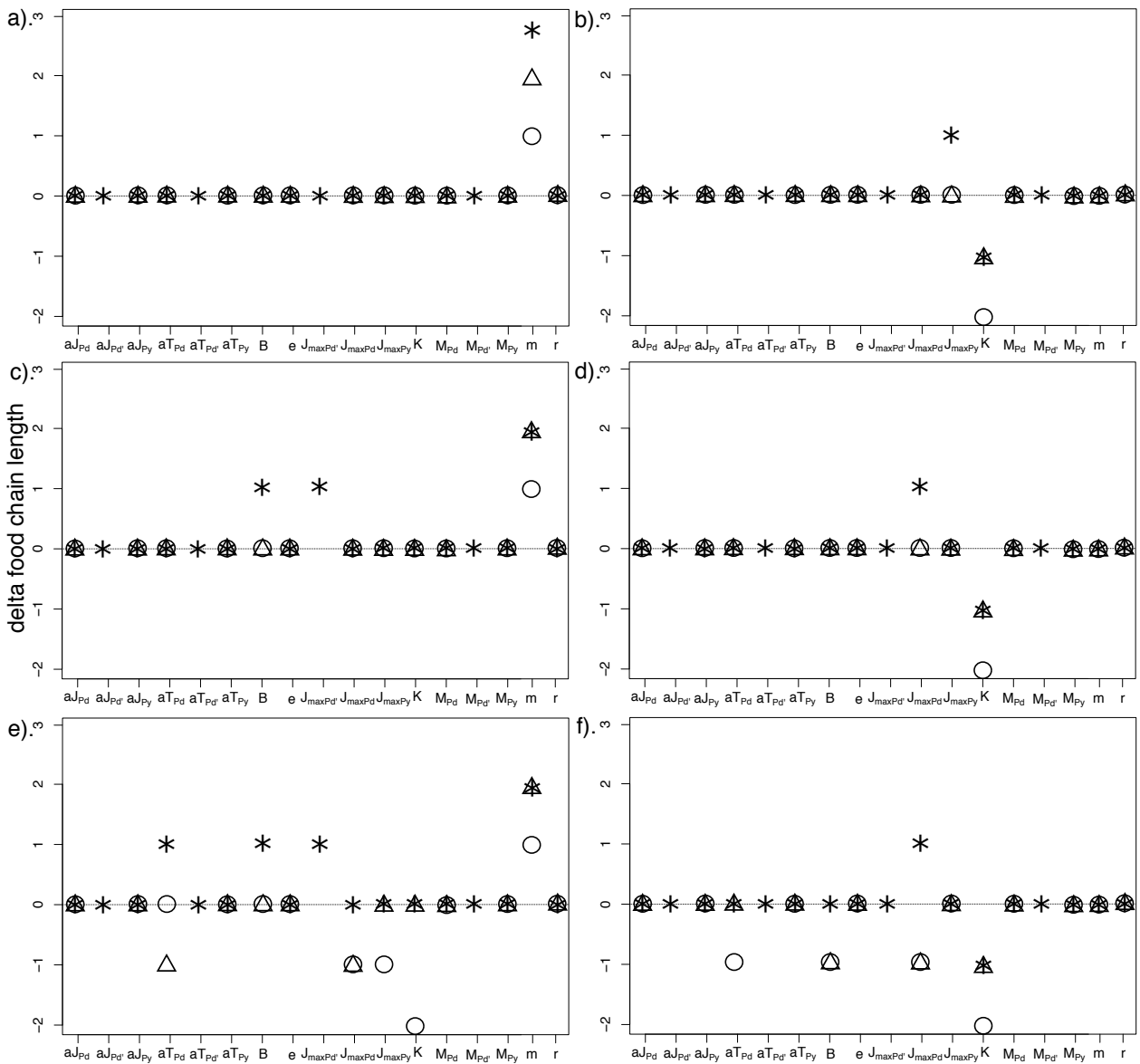


Figure A3. Sensitivity analyses of food web modules at baseline conditions. Circles, triangles, and asterisks depict the observed change in food chain length from baseline conditions for module I, II and III when parameters were altered by: (a) +10% and (b) -10%; (c) +20% and (d) -20%; and (e) +50% and (f) -50%, respectively. If the maximum or minimum possible value of a given parameter was reached with a given increase or decrease then the value was held at its maximum or minimum possible value. Note: $m = 0$ for all decreases in m .

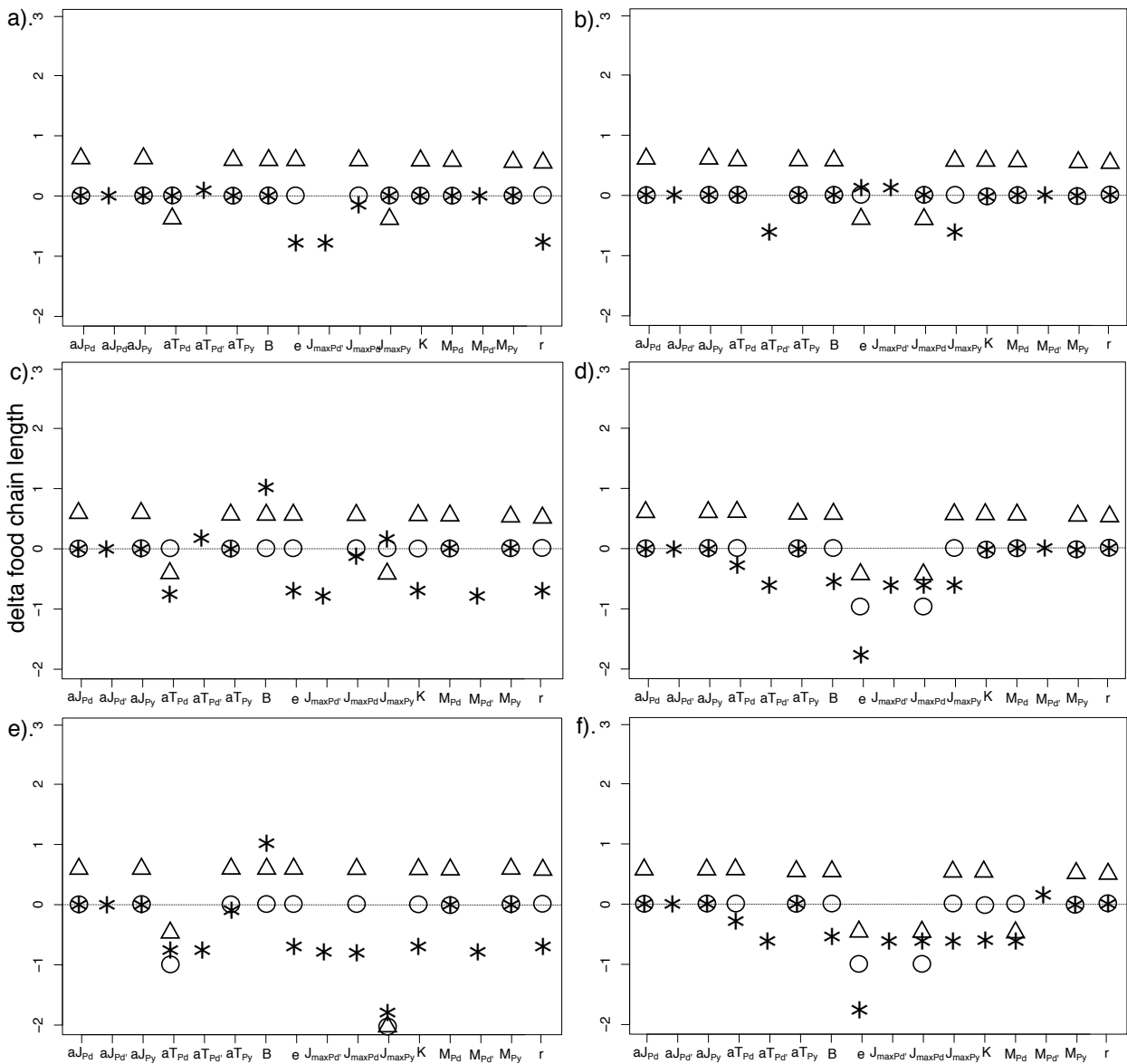


Figure A4. Sensitivity analyses of food web modules when m is increased by 10 percent. Circles, triangles, and asterisks depict the observed change in food chain length from baseline conditions for module I, II and III when parameters were increased and decreased : (a) +10% and (b) -10%; (c) +20% and (d) -20%; and (e) +50% and (f) -50%, respectively. If the maximum or minimum possible value of a given parameter was reached with a given increase or decrease then the value was held at its maximum or minimum possible value. Note: baseline conditions for m and r respectively were 0.1 and 1.

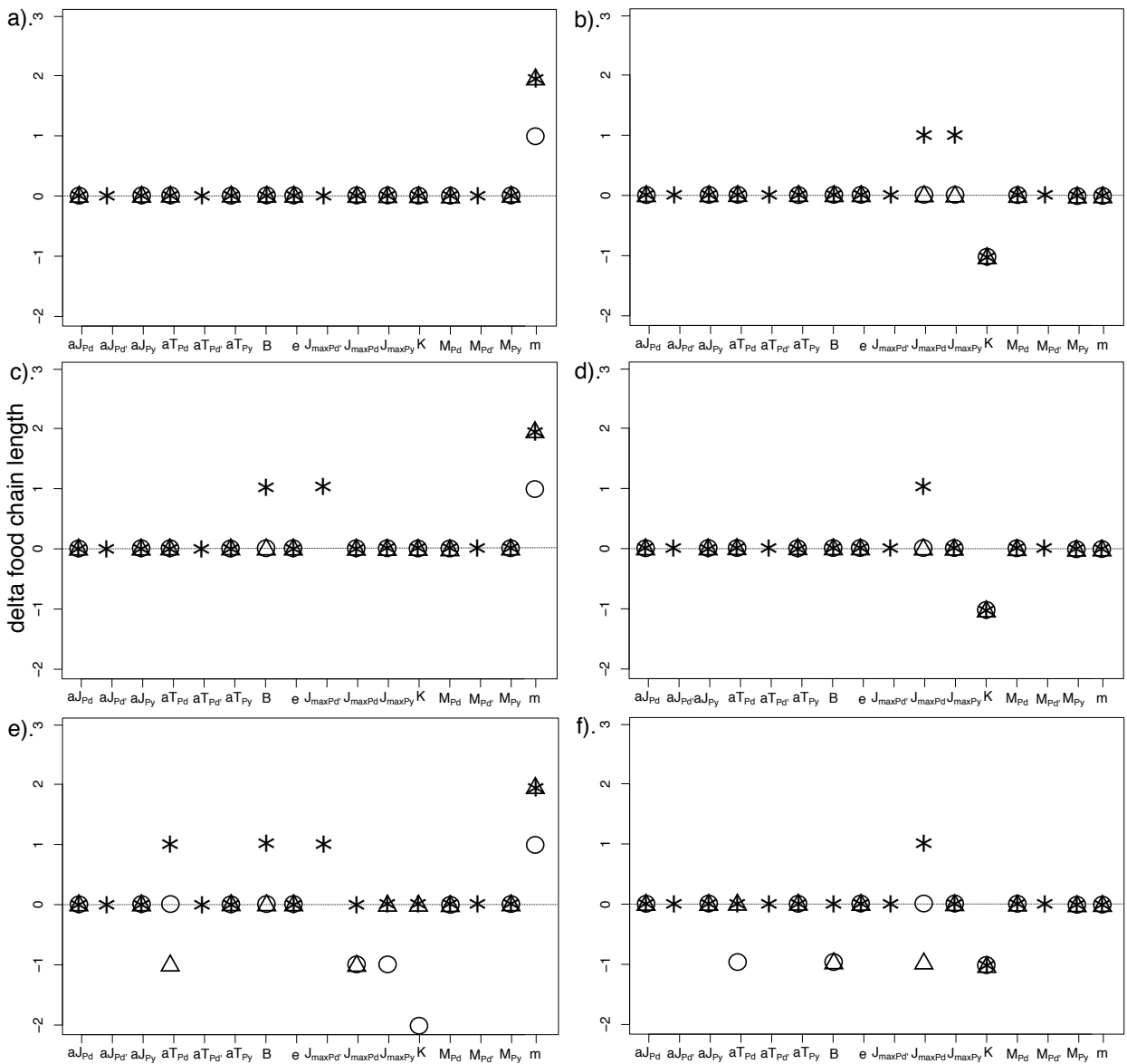


Figure A5. Sensitivity analyses of food web modules when r is increased by 10 percent. Circles, triangles, and asterisks depict the observed change in food chain length from baseline conditions for module I, II and III when parameters were increased and decreased by: (a) +10% and (b) -10%; (c) +20% and (d) -20%; and (e) +50% and (f) -50%, respectively. If the maximum or minimum possible value of a given parameter was reached with a given increase or decrease then the value was held at its maximum or minimum possible value. Note: baseline conditions for m and r respectively were 0 and 1.1.