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Supplement B: Ecopath Parameters and Their Data Sources

This section describes the data sources and methods to derive input parameter values of group-specific biomass (B), production to biomass (P/B), consumption to biomass (Q/B), and diet composition for the Ecopath model of the Lake Erie food web. We present the parameter values in Tables 1, 3–6 in the manuscript.

Phytoplankton

Biomass (B, grams wet weight/m^2) was derived from the Lake Erie Plankton Abundance Study database at the Ohio State University (Conroy et al. 2005). Phytoplankton biomass was the average of all station samples over the sampling seasons. P/B (per year) values for algal groups were calculated from Munawar et al. (2008) assuming 240 days of growing season and were averages of monthly biomass-weighted values.

Picoplankton

Biomass was an average of estimates from two studies (Fahnenstiel et al. 1998; Munawar et al. 2008). P/B values were calculated from Munawar et al. (2008) for the algal group < 2 μm.

Bacteria

Biomass was an average of estimates from two studies (Fahnenstiel et al. 1998; Hwang and Heath 1997). P/B and Q/B values were obtained from Stewart and Sprules (2011).

Protozoa

Protozoa biomass was calculated from Smith et al. (2005). P/B for protozoa was calculated based on Lavrentyev et al. (2004), while consumption to biomass estimates (Q/B, g wet mass of prey $\cdot g^{-1}$ predator biomass $\cdot yr^{-1}$) were calculated based on gross growth efficiency reported by Straile (1997). Diet composition of protozoans was estimated from studies by Vanderploeg (1994) and Hwang and Heath (1997).

Zooplankton

Biomass was derived from the Lake Erie Plankton Abundance Study database at the Ohio State University (Conroy et al. 2005). P/B values were calculated based on published relationships between temperature and production (Shuter and Ing 1997; Stockwell and Johannsson 1997). Specifically, for non-predatory cladocerans, P/B=0.162/d when temperature was >10 ˚C, and 0.042/d when temperature was <10 ˚C (Stockwell and Johannsson 1997); for predatory cladocerans, P/B is a function of body weight and water temperature $\log\left(daily\,\frac{P}{B}\right) = -0.23\log\left(dry\ wt\ (\mu g)\right) - 0.73$, when mean seasonal temperature > 10 ˚C, and $\log\left(daily\,\frac{P}{B}\right) = -0.26\log\left(dry\ wt\ (\mu g)\right) - 1.36$, when mean seasonal temperature < 10 ˚C. For copepods and rotifer, P/B is calculated as: $\log\left(median\ daily\,\frac{P}{B}\right) = A + 0.04336(median\ temperature\ (°C))$, where A = -1.844 for cyclopoids, -2.294 for calanoids, and -1.631 for rotifers (Shuter and Ing 1997). We used water temperature values provided from output of a 1-dimensional model of Lake Erie water temperature by Rucinski et al. (2010). Q/B values were calculated based on gross growth efficiency reported by Straile (1997). Diet for most zooplankton groups was obtained from Vanderploeg (1994), but for *Bythotrephes* spp was obtained from Vanderploeg et al. (1993).

Benthos

Biomass and production values were based on empirical data reported in Johannsson et al. (2000). Dreissenid mussel biomass was obtained from Patterson et al. (2005). We divided P/B estimates from Johansson et al. (2000) by P/Q estimates (see below) to obtain Q/B values for most taxa. P/Q estimates for chironomids, sphaeriids, oligochaetes, and gastropods were reported by Lindegaard (1994); estimates for amphipods were obtained from Nilsson (1974); and estimates for mayflies, caddisflies and dragonflies were obtained from McCullogh et al. (1979). P/B for dreissenid mussels was obtained from the Stewart and Sprules (2011) EwE model of Lake Ontario. P/Q was estimated as the product of the ratio of P to assimilation rate (Hamburger et al. 1990) and the ratio of assimilation rate to Q (Baldwin et al. 2002). Diet information for benthos taxa was obtained from Wetzel (2001). Dreissenid diet was proportional to prey biomass as dreissenids are assumed to be indiscriminant filter-feeders. However, dreissenid consumption of blue green algae was reduced compared to green algae and diatoms due to high buoyancy and rejection rates of blue-green algae by dreissenids (Vanderploeg et al. 2002).

Fish

Ecopath parameters P/B, B, Q/B and diet compositions of most fish groups were estimated using the following general methods. Parameter estimates of fish estimated by different approaches (other methods) are described separately.

Production to biomass ratio (P/B)

General method.—We estimated P/B values for groups of the following fish species based on one or several of the following four equations and availability of existing data. In cases where we estimated P/B using more than one equation, we averaged the P/B values. These species included White Bass (Eqs S.B.1–S.B.4), White Perch (Eqs. S.B.1–S.B.4), Rainbow Trout (Eq. S.B.2), Burbot (Eqs. S.B.2–S.B.3), Smallmouth Bass (Eqs. S.B.1, S.B.4), Alewife (Eqs. S.B.2–S.B.4), Lake Trout (Eqs. S.B.2–S.B.4), Gizzard Shad (Eqs S.B.1, S.B.4), Common Carp (Eqs. S.B.2–S.B.3), Round Goby (Eqs. S.B.2–S.B.3), sucker (Eqs. S.B.2–S.B.4), shiner (Eqs. S.B.2–S.B.3), catfish (Eqs. S.B.2–S.B.3), and panfish (Eq.S.B.2).

$Z = {}^{P}/_{B} = \frac{k(L_\infty - \overline{L})}{\bar{L} - L'}$ (Beverton and Holt 1957; , see in Christensen et al. 2005) (S.B.1)

$Z = 4.31T_{max}^{-1.01}$ (Hoenig 1983) (S.B.2)

$Z = 2.64W_{mat}^{-0.35}$ (Randall and Minns 2000) (S.B.3)

where $\text{Log}(W_{mat}) = -0.762 + 0.931\text{Log}(W_{max})$;

$Z = -\ln(S)$ (CAGEAN, Deriso et al. 1985; Gulland 1983) (S.B.4)

where S is survival rate, T_{max} is the oldest age caught in the surveys; W_{max}, k, L_∞ respectively represent the maximum weight, the Brody growth coefficient, and the maximum length estimated from the von Bertalanffy growth function; $\bar{L}$ is the mean length of fish in the population, and L' is the mean length at entry into the fishery, assuming knife-edge selection (Christensen et al. 2005). We used two index surveys, the Ontario Partnership Gillnet Database (OMNR 2013) and the Summertime Interagency Trawl Database (Tyson et al. 2006; Zhu and Johnson 2008) to estimate parameter values in these equations.

Other methods.—P/B, or total mortality rate (Z) of Walleye and Yellow Perch values were estimated from agency reports, values reported from other lakes, or catch-at-age population models. The P/B value for Walleye age 0-6 months was calculated from survival rates estimated for Walleye in Oneida Lake, NY (Rose et al. 1999). age-0 Walleye P/B was calculated based on equation (Eq. S.B.1) of Beverton and Holt (1957). P/B values for other age classes of Walleye were obtained from the Walleye Task Group 2000 annual report (http://www.glfc.org/lakecom/lec/WTG.htm). Larval and age-0 Yellow Perch P/B values were calculated from survival rates (Rose et al. 1999). The P/B value for age 1 Yellow Perch was estimated based on the survival rate of age-0 Yellow Perch abundance in the late fall (interagency trawl data from Yellow Perch task group, http://www.glfc.org/lakecom/lec/YPTG.htm) to the beginning of age 2 (abundance estimated using ADMB model, Yellow Perch Task Group 2013, http://www.glfc.org/lakecom/lec/YPTG.htm). Freshwater drum P/B was estimated by Bur (1984) from catch curve of freshwater drum caught in trap nets from the western basin of Lake Erie. P/B for rainbow smelt was from studies by Lantry and Stewart (1993).

Biomass (B)

To generate whole lake estimates of fish density, for most fish species we derived density from whole-lake fishery catches and exploitation rates. Walleye and Yellow Perch densities were obtained from ADMB population assessment model output for the whole lake. Density estimates of some prey fish (Emerald Shiner, Gizzard Shad, and Rainbow Smelt) were based on trawl and acoustic data and weighted by basin areas.

Exploitation rate method.—For fishes that are harvested in Lake Erie (Lake Whitefish, White Bass, White Perch, Smallmouth Bass, Freshwater Drum, Alewife, Gizzard Shad, Common Carp, sucker, catfish, and panfish), biomass was estimated based on the relationship between biomass (B, t/km^2), fishery catch (C, t), exploitation rate (μ), and the area of Lake Erie (LA, km^2), assuming the catch data include all removals (Hilborn 2001; Hilborn and Walters 1992),

$$B = (C/\mu)/LA$$

where the exploitation rate μ was estimated from the total instantaneous mortality rate Z (see P/B estimation above), and instantaneous natural (M) (Pauly 1980) and fishing (F) mortality rates.

$$M = K^{0.65} \cdot L_{\infty}^{-0.279} \cdot T_c^{0.463}$$

$$\mu = \frac{F(1-S)}{Z} = \frac{(Z-M)(1-e^{-Z})}{Z}$$

Catch data (C) included commercial fish harvest (Baldwin et al. 2009) and recreational fisheries harvest estimated from creel surveys (ODW 2008; ODW 2011, DFO, http://www.dfo-mpo.gc.ca/stats/rec/great-lakes-eng.htm). By-catch of species was estimated using the gillnet partnership database and fishery catches. Specifically, for each by-catch species, a general linear regression was developed between gram per lift of the fish species (y) and gram per lift of Yellow Perch (x) using the gillnet survey data. Assuming fish species have the same linear relationship with Yellow Perch in fishery catch, by-catch is the difference between the reported fishery catch of this fish species and the predicted catch from the linear regression.

Other methods.—We simulated biomass (B) of 4 age classes of Walleye, specifically for 0-6 months old, 7-12 months (age-0), 13-36 months (juveniles), and >36 months (adults). Biomass of adults was provided by a catch at age analysis and summarized in the Walleye Task Group annual report. We also modeled biomass of 4 age classes of Yellow Perch, specifically 0-6 months, 7-12 months (age-0), 13-24 months (juveniles), and >24 months (adults). Biomass of adult Yellow Perch was estimated from a catch at age population model and reported in the Yellow Perch Task Group annual report. Biomass of other age groups for Walleye and Yellow

Perch was predicted by the multistanza algorithm of EwE based on stock-recruit relationships and age-specific P/B values.

Rainbow Smelt biomass was estimated from time series of bottom trawl data obtained from the Lake Erie Forage Task Group for Lake Erie's western, central and eastern basins. The catchability of bottom trawls was the ratio between the biomass estimated using hydroacoustics and bottom trawl data from Lake Erie's central basin in the 2005 International Field Year study of Lake Erie. Hydroacoustics data were processed following the standard operating procedures for fisheries acoustic surveys in the Great Lakes (Parker-Stetter et al. 2009). The acoustic estimate of fish density was partitioned among fish species that were collected using mid-water trawls at the same time and on the same transects. Fish density was converted into wet biomass using length-weight regressions. We assumed this biomass estimate is the true water column biomass of rainbow smelt. The ratio between the biomass estimated from the hydroacoustics and bottom trawl data in Lake Erie's central basin in 2005 is catchability. We used this catchability ratio to estimate the biomass of rainbow smelt from bottom trawl data for 1999, the period of our Ecopath model. The lake-wide biomass is the average biomass of the three basins weighted by area.

Round Goby abundance and biomass were estimated to be 9.89 billion individuals and 25,048 t in western Lake Erie between June and October 2002 (Johnson et al. 2005a). The goby abundance was 2.2 billion in Lake Erie's central basin between 2000 and 2002 (Johnson et al. 2005b). Assuming the average weight of a Round Goby individual is the same for the same year in the central basin as in the western basin, the biomass of Round Goby in the central basin was 5571.85 t. We then assumed the area density of goby in the eastern basin was the same as that in the eastern basin, and estimated the total biomass of Round Goby in eastern basin to be 2152.71 t. Our estimate of the overall lake-wide average biomass of Round Goby was 1.28 g/m.

Our trophic group 'shiner' was comprised mainly of Emerald Shiner. Only in the western basin did spottail shiner comprise about 10% of the total western basin shiner biomass. We calculated biomass of Emerald Shiner using hydroacoustic estimates from Lake Erie's central basin in 2005, then calculated catchability of shiner in bottom trawls and obtained a basin-wide estimate as we did for Rainbow Smelt.

Lake Trout biomass was estimated using the 2006 revised Lake Erie Population Model. Rainbow Trout (Steelhead) biomass was estimated from Kayle (2007). Burbot biomass was based on Ontario Partnership Gillnet Database data and catchability of another demersal species, adult Yellow Perch.

Consumption to biomass ratio (Q/B)

Q/B values for adult Walleye were calculated as biomass-weighted average Q/B values of different ages from age 3 to age 7+. Q/B of each age class was the average of estimates from two methods: one estimate was provided by a bioenergetics model of Walleye (Hartman and Margraf 1992), and the other method was based on the following empirical regression for fish groups (Palomares and Pauly 1998):

$$\log\left(\frac{Q}{B}\right) = 7.964 - 0.204 \cdot \log W_{\infty} - 1.965 \cdot T' + 0.083 \cdot A + 0.532 \cdot h + 0.398 \cdot d$$

where W_{∞} is the asymptotic weight (g), T' is an expression for the mean annual temperature of the water body, expressed using $T' = \frac{1000}{T(℃)+273.15}$, A is the aspect ratio of the caudal fin, h is a dummy variable expressing food type (1 for herbivores, and 0 for detritivores and carnivores), and d is a dummy variable (1 for detritivores, and 0 for herbivores and carnivores). Q/B for adult

Yellow Perch was calculated as the biomass-weighted average Q/B value of different ages from age 2 to age 6+, based on Palomares and Pauly's relationship (1998).We also applied this approach to estimate Q/B for the following fish groups: Burbot, White Bass, White Perch, Smallmouth Bass, Freshwater Drum, Alewife, Gizzard Shad, Round Goby, sucker, shiner, catfish and panfish. Q/B for Rainbow Smelt was based on estimates of gross conversion efficiency (Lantry and Stewart 1993).

Diets

General method.—We estimated diet composition of fishes using studies of fish diets from Canadian waters of all three basins (Cook et al. 1997; Mullowney 2002). Diet data from Cook et al. (1997) included samples from June to October 1995 and from May to June 1996. They examined diets of Walleye, Yellow Perch, White Perch, White Bass, Smallmouth Bass, Freshwater Drum, Burbot, Rainbow Trout, and Channel Catfish. From 1999 through 2001, Mullowney (2002) sampled diets of Walleye, Yellow Perch, Smallmouth Bass, White Bass, and Rainbow Trout. We averaged available diet composition data for the above species from these studies across years, months, and basins to serve as input for the Ecopath model.

Other methods.—Lake whitefish diet data were obtained from the coldwater task group (Cold Water Task Group [2002] annual report [http://www.glfc.org/lakecom/lec/CWTG.htm]). We obtained Burbot diet composition data from Cook (1997) and Cold Water Task Group (2013, http://www.glfc.org/lakecom/lec/CWTG.htm) from 1999 to 2003. Lake Trout diets were estimated from Cold Water Task Group diet data from 1999 to 2003 (http://www.glfc.org /lakecom/lec/CWTG.htm). There are no published studies of Common Carp diets in Lake Erie, so we used diet data from Lake Banyoles, Spain (Garcia-Berthou 2001), and Lake Balaton, Hungary (Specziar et al. 1997). Alewife diet data were based on studies by Mills et al. (1992, 1995), and Strus and Hurley (1992). Diet of Round Goby was estimated by Johnson et al. (2005b) and Lee (2003). There were no diet data available for suckers in Lake Erie, so we used diet data from a study in Salt River and Slave River, Canada (Little et al. 1998), and in Missouri River, North Dakota (Welker and Scarnecchia 2003). Diet information for Emerald Shiner was obtained from Hartman et al. (1992) and Pothoven et al. (2009). Diets of panfish including Black Crappie, Pumpkinseed, and Rock Bass were based on studies by French (1988) and Liao et al. (2002). Diet of Rainbow Smelt was based on studies by Stetter et al. (2005) and Pothoven et al. (2009). Gizzard Shad diet was reported by Prince (1963). Kayle (2007) reported diet data of rainbow trout.

Waterbirds

Production to biomass ratio.—Cormorant P/B was estimated as the average from two methods. The first method assumed 60% of the breeding population produced 1 fledgling chick annually resulting in an annual population increase of 30% (P/B=0.3). The second method used Hoenig's (1983) Equation 2 assuming the maximum age of double-crested cormorants is 18 years (Hatch and Weseloh 1999), resulting in a P/B=0.23. We used Hoenig's (1983) equation to calculate merganser P/B =0.4380, which is an average of P/B for red-breasted merganser (longevity is 9 years) and common merganser (13 years).

Biomass.—We used the number of nests to calculate bird abundance (Bundy et al. 2000; Morissette et al. 2003). We estimated cormorant biomass as the product of population abundance multiplied by average individual biomass, 2.28 kg (Hebert and Morrison 2003; Madenjian and Gabrey 1995; Rudstam et al. 2004). Although cormorants are aggregated in the western and eastern basins, for this analysis we assumed the birds are evenly distributed throughout Lake Erie basins, and B is 0.046 kg/ha. We followed the same procedure to estimate biomass of mergansers as we did for double-crested cormorants. We used the number of nests and the average individual biomass (0.71kg for red-breasted mergansers, 1.65 kg for common mergansers, Madenjian and Gabrey 1995, Hebert and Morrison 2003) to estimate the biomass at B = 0.12 kg/ha, assuming the birds were evenly distributed throughout Lake Erie basin..

Consumption to biomass ratio - For cormorants, we estimated Q/B as an average of four studies: Hebert and Morrison's (2003) bioenergetics analysis of Lake Erie waterbirds (Q/B = 71.04); Madenjian and Gabrey's (1995) bioenergetics analyses of Lake Erie waterbirds (Q/B = 45.08); Rudstam et al.'s (2004) estimate of cormorant consumption in Oneida Lake NY (Q/B = 71.79); and Blukacz-Richards and Koops' (2012) estimate of cormorant consumption in the Bay of Quinte, Lake Ontario (Q/B= 85.78). We estimated merganser Q/B = 29.81 per year based on Hebert and Morrison (2003).

Cormorant diet composition was assumed to be the mean of diet composition reported in studies by Bur et al. (1999), Hebert and Morrison (2003), and Johnson et al. (2000, 2001). Merganser diet composition was taken from mean values of diets reported in studies of Hebert and Morrison (2003) and Bur (2008).

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