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Integrative demographic modeling reveals population level impacts of PCB toxicity to juvenile snapping turtles

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ABSTRACT

A significant challenge in ecotoxicology and risk assessment lies in placing observed contaminant effects in a meaningful ecological context. Polychlorinated biphenyls (PCBs) have been shown to affect juvenile snapping turtle survival and growth but the ecological significance of these effects is difficult to discern without a formal, population-level assessment. We used a demographic matrix model to explore the potential population-level effects of PCBs on turtles. Our model showed that effects of PCBs on juvenile survival, growth and size at hatching could translate to negative effects at the population level despite the fact that these life cycle components do not typically contribute strongly to population level processes. This research points to the utility of using integrative demographic modeling approaches to better understand contaminant effects in wildlife. The results indicate that population-level effects are only evident after several years, suggesting that for long-lived species, detecting adverse contaminant effects could prove challenging.

1. Introduction

Despite the ban on PCBs imposed in the U.S. in 1979, PCBs continue to impact species in contaminated habitats due to their persistence and historically wide use. The upper Hudson River, for example, is characterized by high levels of PCB contamination that resulted primarily from historical discharges from two electric capacitor plants operated by the General Electric Corporation (see Baker et al., 2006; NOAA, 2013). The PCB contaminated region of the Hudson River is occupied by many species of wildlife and thus there has been a long-standing concern that PCBs may deleteriously impact resident organisms. PCBs can exert a number of toxic effects on exposed animal species including disruption of endocrine function, immunotoxicity, developmental effects and alterations in metabolism (Hoffman, 2003), any of which may impact fitness by reducing survival, growth or reproductive success.

Previous research on common snapping turtles, *Chelydra serpentina*, from the upper Hudson River, NY, USA showed that turtles from PCB-contaminated habitats experienced reduced juvenile survival and growth that manifested long after hatching, representing significant latent effects (Eisenreich et al., 2009). Specifically, by 14 months post hatch, only 40% of laboratory-reared juveniles obtained from mothers from the most PCB contaminated portion of the Hudson River survived, compared to 90% of juveniles obtained from mothers from uncontaminated areas (Eisenreich et al., 2009). Growth was also affected by maternally transferred PCBs: the post-overwintering size of hatchlings from PCB-exposed mothers was significantly smaller than hatchlings from reference sites (Eisenreich et al., 2009). Although effects of PCBs have been observed in other species (Aulerich and Ringer, 1977; Örn et al., 1998; Harris and Elliott, 2011), the study by Eisenreich et al. (2009) is among the few studies on PCB exposure and effects in wild turtles. Another laboratory study has also shown that PCBs can decrease growth rates in juvenile turtles (*Malaclemys terrapin*; Holliday et al., 2009) and the observed effect may, in part, be mediated by affects on bone density (Holliday and Holliday, 2012). Despite the strong and obvious indicators of PCB toxicity to turtles, uncertainties remain regarding how these effects observed in juvenile turtles may manifest at the population level.

A primary objective in ecotoxicology and ecological risk assessment is to determine at what level of contaminant exposure natural populations might show adverse effects. Ideally, inferences obtained from laboratory or field studies can be clearly linked to expected effects in wild populations although, in practice, this link can be difficult to establish (Forbes et al., 2008). Population-level

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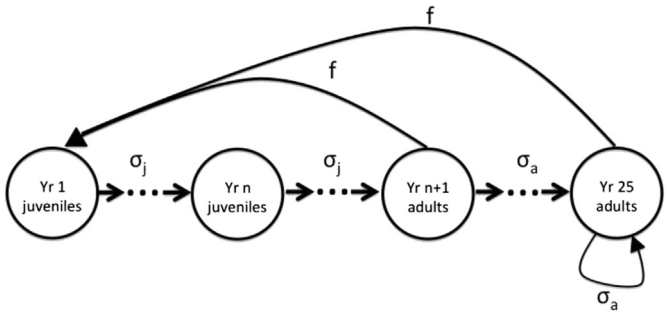

Fig. 1. Life cycle graph for snapping turtles. The self-loop for age 25 adults represents adult turtles that live beyond 25 years with no pre-determined maximum age. The n, determined from the Von Bertalanffy growth curve, represents the last juvenile stage while $n + 1$ is the first year of reproduction – note that these are variable but longer than 1 year as indicated by the dotted lines between classifications (e.g., Yr1 juveniles and Yr n juveniles). Juvenile and adult stages are identical with σ_j and σ_a representing the probabilities of survival, respectively. Recruitment to year 1 juveniles is represented by f and is calculated from breeding frequency, clutch size, hatching success and survival of year 0-year 1 juveniles adjusted for the fraction of the year spent as a hatchling turtle.

approaches that include demographic models, however, have gained considerable traction in ecotoxicology and risk assessment and are valuable for improving our understanding of ecotoxicological effects (Forbes and Calow, 1999; Barnthouse et al., 2008; Forbes et al., 2008; Salice et al., 2011a; Hanson and Stark, 2012). A key advantage of population-level assessments is that outputs from the assessment can directly relate to and inform management objectives. Specifically, population models yield outputs such as population growth rate, population size and extinction risk, and can be used to assess the effects of contaminants on these endpoints. These outputs can be used to describe whether under a certain set of conditions, a population may be growing or declining and how contaminant effects may alter the potential of the population to respond to other stressors (e.g., Salice et al., 2011a).

While population-level assessment can provide insights into ecological effects of contaminant exposure, they are also more data intensive compared to other risk estimators, especially hazard or risk quotients (Forbes et al., 2008; Salice et al., 2011b). At a minimum, life history data on the schedules of survival, growth and reproduction are needed to parameterize population models. Any potential impacts of contaminants can be explored at the population level by altering particular life cycle traits according to laboratory or field data. For snapping turtles, life history traits have been well studied (Christiansen and Burken, 1979; Congdon et al., 1987, 1994; Galbraith et al., 1989) providing the necessary data for constructing models for meaningful analysis of population-level effects of contaminants.

Our objective here was to explore the potential population-level effects of observed PCB effects on juvenile survival and growth in common snapping turtles obtained from a population in the Hudson River. Based upon previous long-term studies of snapping turtle life histories, we constructed and parameterized a combined age- and stage- structured demographic model. As well, we explored the impacts that PCBs might have on time to reproduction by developing a growth model that we then altered to reflect potential effects of PCBs based on studies of growth of PCB exposed diamondback terrapins (Holliday et al., 2009; Holliday and Holliday, 2012). Population growth rate and population size through time were specifically included as outputs. We discuss the results in light of the uncertainties and provide recommendations for future study and management action.

2. Model description

We developed a combined age- and stage-based demographic matrix model for snapping turtles to evaluate the impact of PCB-induced effects on hatching success and juvenile size and growth rate that might modify time to maturity and, hence, population growth rate (Fig. 1). The model was parameterized from previously published life history data for the common snapping turtle, *Chelydra serpentina* (Christiansen and Burken, 1979; Congdon et al., 1987, 1994; Galbraith et al., 1989). Time to female maturity was based on reaching a size of 20 cm carapace length and was determined using the Von-Bertalanffy growth model parameterized from a growth study of snapping turtles from an Ontario, Canada population (Galbraith et al., 1989; Table 1; Fig. 2). The growth data were fitted to the Von-Bertalanffy growth equation using nonlinear least squares in R. Based on the growth model, average time to maturity was 12 years for turtles from a reference (REF) population not exposed to PCBs. This average time to maturity estimated from the growth model was consistent with field data on snapping turtles (Christiansen and Burken, 1979; Galbraith et al., 1989; Congdon et al., 1994). We then used the growth equation to estimate time to maturity from hatchling size measurements based on data from Eisenreich et al. (2009). The complete matrix model included 24 age classes and a stage 25 that had a self loop and represented "older adults." Hence, there was no maximum lifespan specified in the model.

Survival and clutch size data used for the demographic model were obtained from a complete snapping turtle life table for a population in Michigan (Congdon et al., 1994). The model was female only and assumed an equal sex ratio. The time step of the model was one year. Table 1 includes all model parameter values along with estimates of variability, where appropriate or when available. We did not include any density dependence in the model, as field data and model analysis does not suggest that snapping turtle populations are subjected to strong density dependent survival or reproduction (Brooks et al., 1991; Congdon et al., 1994).

The effects of PCBs on snapping turtle juvenile survival and size observed by Eisenreich et al. (2009) served as the basis for this population-level analysis. The effects of PCBs included in the model related to reductions in hatching success, hatchling size and hatchling/juvenile (Year 1 and 2) survival (Table 1). We also separately evaluated projected impacts of PCBs on growth beyond year 2 juveniles by assuming a 5, 10 or 15% reduction in yearly growth rate in PCB-exposed snapping turtles. This evaluation of a PCB-induced effect on growth rate is justified based on observed impacts of PCBs on snapping turtles (Eisenreich et al., 2009) as well as effects of PCBs on growth rates in diamondback terrapins (Holliday et al., 2009; Holliday and Holliday, 2012). Specifically, Holliday et al., 2009 observed significant effects on growth and metabolism following intraperitoneal injection of PCBs to diamondback terrapins. They observed approximately an 11% decrease in growth over the 180 day exposure period in PCB-exposed turtles. An important potential demographic effect of slower growth is a later time to reproductive maturity, which can directly reduce population growth rate. To estimate time to reproductive maturity we used the Von Bertalanffy growth equation to determine number of years to reach reproductive size. We assumed no effects of PCBs on adult survival or clutch size (Kelly, 2007) although it is possible that PCBs could affect both of these vital rates (see Bishop et al., 1991).

Two series of simulation analyses were conducted. In the first, we explored the impacts of PCBs on population growth rate (PGR) and incorporated variability in vital rates by sampling randomly from distributions described by the mean and standard deviation (Table 1). One thousand simulations were conducted that essentially amounted to 1000 different population projection matrices