Amphibia-Reptilia 30 (2009): 259-264

Predicted climate change may spark box turtle declines

Malcolm L. McCallum[1,*], Jamie L. McCallum[2], Stanley E. Trauth[3]

Abstract. How will organisms deal with Climate change? Ectotherms such as reptiles and amphibians are especially at risk due to their metabolic ties to the environment and their general inability to migrate with changing climates over short time frames. We modeled the growth response of Three-toed Box Turtles (*Terrapene carolina triunguis*) to fluctuations in ambient temperature and precipitation. Then we extrapolated this model to climate conditions expected in 2100. We predict that there is less than 20% possibility of hatchling turtles growing during their first year. Reduced annual growth rates during later years may cause earlier termination of growth, smaller standard carapace lengths, and reduced fecundity. These responses are typical of those that stimulate an extinction vortex. These findings provide for a general understanding of how this species and other terrestrial reptiles may respond to climate change. Without reduction in greenhouse gas emissions we could face catastrophic declines in many ectotherms as temperature and rainfall patterns change.

Keywords: extinction, fuzzy regression, growth, reproduction, risk assessment.

Introduction

Our actions are rapidly transforming the global climate (American Association for the Advancement of Science [AAAS], 2007). This is forcing asymmetrical regional changes in weather patterns on a global scale (Flato and Boer, 2001). Recent studies demonstrate how these changes may influence the distributions of amphibians and reptiles (Campbell et al., 2004; Martinez-Meyer, 2005; Araujo et al., 2006) and their habitats (LaBaugh et al., 1996; Piha et al., 2007). Climate change may explain earlier occurring anuran breeding chouruses (Gibbs and Breisch, 2001; Green et al., 2001), changes in turtle sex ratios (Janzen, 1994), and local range shifts up mountain slopes (Seimon, 2007). Despite this, relatively few studies exist that target amphibians and reptiles (Parmeson et al., 2000; Parmeson, 2006). Life history parameters provide the foundation for constructing wise conservation practices that we need to identify and circumvent the possible negative influences of climate change (Bury, 2006; McCallum and McCallum, 2006).

How terrestrial ectotherms respond to climate change is a concern because their metabolism responds closely to ambient temperatures (Zug et al., 2001). Reptiles, such as turtles, are a special concern because we expect climate change to stimulate their population declines (Gibbons et al., 2000). Few amphibians or reptiles are likely to follow shifting climates because most do not have the migratory prowess of other organisms such as birds, mammals, and many fishes (Parmesan, 2006). This leaves these groups subject to the changing climates with little time available for adaptation (Rahel et al., 1996). Some species have already succumbed to shifting climates (Pounds and Crump, 1994; Pounds et al., 1999; Pounds, 2006).

We used the Three-toed Box Turtle (*Terrapene carolina triunguis*) as a model ectotherm to investigate if predicted climate change may influence body growth and fecundity. If this is true, we predicted that we could construct regression models to accurately describe temperature and precipitation influences on turtle growth ($\alpha = 0.05$), and then extrapolate future responses due to climate change.

---

1 - College of Arts, Sciences and Education, Texas A&M University-Texarkana, 2600 Robison Road, Texarkana, TX 75501, USA

2 - 117 Linda Lane, Texarkana, TX 75501, USA

3 - Department of Biological Sciences, Arkansas State University, State University, AR 72467, USA
*Corresponding author; e-mail: malcolm.mccallum@ herpconbio.org

Materials and methods

We collected Three-toed Box Turtles ($n = 35$) from 1965-2006, with 34% of these collected before 2000, from southwestern Arkansas. We aged each turtle using the growth rings from the left pectoral plastral scute, and then back-calculated annual growth using biochronology techniques (Germano, 1993; Tucker et al., 1995). The utility of major growth rings for age and growth determination in turtles is well supported (Germano, 1993; Germano and Bury, 1998; Converse et al., 2005; Budischak et al., 2006), although some debate its validity (Wilson et al., 2003). Its potential use for examination of environmental effects on growth has been discussed (Tucker et al., 1995).

We obtained seasonal temperatures and precipitation for 1901-2006 from the NOAA (National Oceanic and Atmospheric Association) online database and used multiple linear regression and best subsets regression to model interactions between these climate variables and growth (Neter et al., 1996). We constructed fuzzy sets using the average precipitation and temperatures observed from 1901-2000 and that predicted for 2100 in Arkansas (table 1; U.S. EPA, 1998). The utility of fuzzy sets in these kinds of studies is well established (see Silvert, 1997; McCallum, 2007). We used RAMAS RiscCalc to calculate average standard carapace length from the fuzzy regressions (Ferson et al., 1999). We used the fuzzy sets from 1901-2000 to create a fuzzy regression model where the variables were fuzzy (Taheri, 2003) to validate the accuracy of the model. Then we repeated these calculations using the data for 2100 to estimate growth in the first year and over the turtle's lifetime.

Results

Does precipitation and temperature influence first-year growth?

The best model included all predictors except summer and fall temperature (Linear Regression: $r^2 = 0.440$, $F_{6,28} = 3.67$, $P < 0.01$):

$$\mathrm{G_1} = 15.5 + 2.45\mathrm{T_{spr}} - 1.33\mathrm{T_w} - 9.237\mathrm{P_{spr}} - 0.604\mathrm{P_{sum}} - 0.283\mathrm{P_f} + 0.504\mathrm{P_w},$$

where $\mathrm{G_1}$ = first year growth (mm), $\mathrm{T_{spr}}$ = average spring temperature (°C), $\mathrm{T_w}$ = average winter temperature (°C), $\mathrm{P_{spr}}$ = average spring precipitation (cm), $\mathrm{P_w}$ = average winter precipitation (cm).

If climate change moves forward as predicted, there is less than 20% possibility that hatchling turtles will show positive growth during their first year (fig. 1).

Does precipitation and temperature influence annual growth at all ages?

The best model was ($r^2 = 0.367$, $F_{5,417} = 48.43$, $P < 0.001$):

$$\mathrm{G} = 15.4 - 0.946\mathrm{A} + 0.765\mathrm{T_{spr}} - 0.961\mathrm{T_w} - 0.096\mathrm{P_{sum}} - 0.102\mathrm{P_f},$$

Table 1. Average seasonal temperature (°C) and precipitation (cm) data observed from 1901-2007 (NOAA, 2000), predicted due to climate change by 2100 (U.S. EPA, 1998), and the associated fuzzy numbers. The mean/best column refers to the average from 1901-2007 or the best estimate from the United Kingdom Hadley Center's Climate Model (HadCM2).

	Low	Mean/Best	High	Fuzzy number
Mean Winter Temperature 1901-2007	1.28	5.42	9.11	[1.28, 5.42, 9.11]
Mean Spring Temperature 1901-2006	13.60	15.74	17.61	[13.60, 15.74, 17.61]
Mean Summer Temperature 1901-2006	24.28	26.04	26.33	[24.28, 26.04, 26.33]
Mean Fall Temperature 1901-2006	13.50	19.34	19.56	[13.50, 19.34, 19.56]
Mean Winter Precipitation 1901-2007	10.26	30.86	58.62	[10.26, 30.86, 58.62]
Mean Spring Precipitation 1901-2006	6.21	14.90	26.83	[6.21, 14.90, 26.83]
Mean Summer Precipitation 1901-2006	10.64	28.07	44.78	[10.64, 28.07, 44.78]
Mean Fall Precipitation 1901-2006	11.61	28.75	58.65	[11.61, 28.75, 58.65]
Predicted Winter Temperature 2100	5.97	6.01	8.74	[5.97, 6.01, 8.74]
Predicted Spring Temperature 2100	16.32	17.43	18.54	[16.32, 17.43, 18.54]
Predicted Summer Temperature 2100	26.60	27.15	29.37	[26.60, 27.15, 29.37]
Predicted Fall Temperature 2100	17.14	18.25	19.36	[17.14, 18.25, 19.36]
Predicted Winter Precipitation 2100	10.26	30.86	58.62	[10.26, 30.86, 58.62]
Predicted Spring Precipitation 2100	39.58	43.35	47.12	[39.58, 43.35, 47.12]
Predicted Summer Precipitation 2100	30.73	34.93	39.12	[30.73, 34.93, 39.12]
Predicted Fall Precipitation 2100	30.38	33.27	36.16	[30.38, 33.27, 36.16]

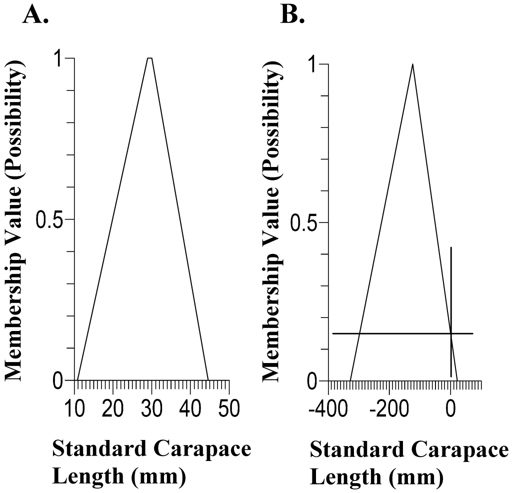

Figure 1. First year growth of the Three-toed Box Turtle (*Terrapene carolina triunguis*) in response to recent climate conditions (A) and the conditions predicted for 2100 (B). The possibility of any hatchling growth is less than 20% (see crossed lines).

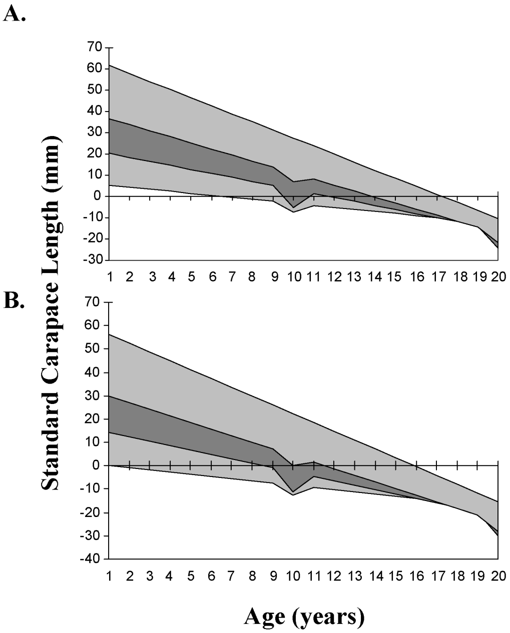

Figure 2. Fuzzy model projections of average Standard Carapace Length (SC) of Three-toed Box Turtle (*Terrapene carolina triunguis*) by age under the climate conditions existing from (A) 1901-2000 and the (B) conditions predicted for 2100. The light gray areas represent standard carapace lengths where membership values approach zero. The dark gray areas represent standard carapace where membership values = 1.

where G = total growth at age "A" (mm), A = age (years), P_{sum} = average summer precipitation (cm), P_f = average fall precipitation (cm).

The fuzzy model predicted the expected age when growth ceases (12-14 yr) under normal climates. This is identical to repourts from Florida (Dodd, 2001) and similar to observations in North Carolina (10-15 yr; Budischak et al., 2006) and New York (12-14 yr; Nichols, 1939). Growth may stop around 8-10 yr under the climate scenario predicted for 2100 (fig. 2). We predicted an average terminal SCL = 123.71 − 151.59 mm using the average climate variation observed 1901-2000; whereas we obtained a terminal SCL = 109.18 − 136.21 mm using climate predictions for 2100.

Discussion

The first year survivourship of hatchling turtles looks bleak. None of the positive first year growth predictions have membership values higher than 20%. This is incredibly low (Silvert, 1997; McCallum, 2007). The highest membership values belong to strongly negative growth rates, suggesting that hatchling turtles experience a negative energy balance resulting in minimal or no growth, and possibly death. If any turtles survive past their first year, we expect little annual growth, leading to reduction in SCL by as much as 10-12%. Earliest maturity in both sexes occurs between 90-100 mm in Florida, and adult *T. c. triunguis* have a CL from 113-150 mm Kansas (Dodd, 2001). Arkansas turtles reach this size around 9 yr. However, there is much variation in size at maturity in turtles (Gibbons, pers. comm.). There is high risk of Arkansas Three-toed Box Turtles ceasing growth prior to reaching a size or age acceptable for normal reproduction.

These results are comparable to previous research. Arctic Charr (*Salvelinus alpinus*) interannual growth responded closely to fluctuations in temperature and precipitation (Kristensen et al., 2006). They concluded that effect of climate change in their populations were dependent on the magnitude of change and on local morphometry of the water body involved. They made no attempt to extrapolate their results. Our study determined that Three-toed Box Turtles also respond to climate flux in a complex manner. Arctic Charr showed responses to average annual temperatures. This is a much more generalized pattern than seen in our study. Three-toed Box Turtles responded to changes occurring in specific seasons. This is a much more complex relationship that may be much harder to observe or study.

Interestingly, the results appear to be counter to those observed in *Chrysemys picta* (Frazer et al., 1991). The investigators speculated that enhanced growth rates and population density resulted from warmer and drier weather during the 1980s. However, differences in how *T. carolina* and *C. picta* respond to climate change are expected. One is a terrestrial species that frequently remains hidden under debris and forest cover, whereas the other is an aquatic species that frequently basks for long hours in the direct sun. These behavioural differences alone suggest that these two species should differ in their response to climate perturbations. However, hatchlings of both species are known to overwinter in the nest (Madden, 1975; DePari, 1996), providing an area of similar exposure to climate.

These results might have serious repercussions for Three-toed Box Turtle populations, and ectotherms in general. Larger *T. c. carolina* produce larger clutches (Kipp, 2003). Therefore, smaller adults could produce smaller clutches, reducing the reproductive output of populations in this region. Furthermore, poor survival of hatchlings and suppressed growth in all age classes could disrupt population structure (Plummer, 2006; Walde et al., 2006; Braun-McNeill et al., 2007), and age-specific reproduction (Kipp, 2003) and survival rates. These population changes are known to stimulate extinction vortices (Soule and Mills, 1998).

It is possible for rapid evolution (Thompson, 1998) of characters that are adaptive to a future changing climate. Rapid evolution has been reported in many species. *Drosophila subobscura* clinally increased wing length with latitude over two decades of dispersal following its introduction into North America (Huey et al., 2000). *Diaptomus sanguineus* (Hairston and Walton, 1986) shifted the timing of diapause in response to pond-drying after a single year, whereas, populations in control ponds did not demonstrate this change. However, evolution in Testudines does not appear to proceed especially fast. In fact, the microevolutionary rate for turtle mitochondrial DNA (mtDNA) has slowed over evolutionary time (Avise et al., 1992), and may reflect the potential for rapid adaptation (Simons, 2002) to climate change. The investigators postulated that the long generation length and low metabolic rate characterizing most turtle species as an “intriguing correlate”. Rapid evolution appears to be unreported or untested in turtles.

Certainly, our proposed model is simplistic and box turtles may make physiological, behavioural or ecological adjustments to deal with climate change. However, the purpose of this model is not to dissect the detailed interactions of this species’ intricate ecology, but rather to examine the role of two major drivers of growth and reproduction, temperature and precipitation. Furthermore, our approach is not intended to model a probability of what will happen, but rather provide a risk assessment of what is possible. Hence, this study should stimulate future investigations to more thoroughly dissect and clarify the intricate relationships pertinent to this problem.

It seems likely that responses by ectotherms to seasonal perturbations in climate vary among species; but it is prudent to assume that many groups may be significantly affected by these kinds of changes. If other species of reptiles and amphibians respond in similar negative ways, we may expect widespread accelerated global extinction of ectotherms. Terrestrial ectotherms such as amphibians and reptiles are major components of a forest’s biomass (Burton and Likens, 1975) and play pivotal roles in ecosystem services (Myers, 1996; Schlaepfer et al., 1999; Balvanera et al., 2001). If climate change ensues at its current rate, it is unlikely that lowly vagile organisms such as terrestrial amphibians and reptiles will have sufficient time to escape these changes by following changing shifts to other regions. Hopefully, we can reduce greenhouse gas emissions in time to reduce the potential impacts of climate change on our biosphere.

Acknowledgements. Thank you to R.B. Bury and W.E. Meshaka for comments on earlier forms of this manuscript. Thank you to B. Silvert for information on the use of fuzzy models.

References

AAAS (American Association for the Advancement of Science) (2007): AAAS Board Statement on Climate Change. Available at http://www.aaas.org/news/press_room/climate_change/mtg_200702/aaas_climate_statement.pdf.

Araujo, M.B., Thuiller, W., Pearson, R.G. (2006): Climate warming and the decline of amphibians and reptiles in Europe. J. Biogeogr. **33**: 1712-1728.

Avise, J.C., Bowen, B.W., Lamb, T., Meylan, A.B., Bermingham, E. (1992): Mitochondrial DNA evolution at a turtle's pace: evidence for low genetic variability and reduced microevolutionary rate in the Testudines. Mol. Biol. Evol. **9**: 457-473.

Balvanera, P., Daily, G.C., Erlich, P.R., Ricketts, T., Bailey, S.A., Kark, S., Kremen, C., Pereira, H. (2001): Conserving biodiversity and ecosystem services. Science **291**: 2047.

Braun-McNeill, J., Sasso, C.R., Avens, L. (2007): Estimates of realized survival for juvenile Loggerhead Sea Turtles (*Caretta caretta*) in the United States. Herpetological Conserv. Biology **2**: 100-105.

Budischak, S.A., Hester, J.M., Price, S.J., Dorcas, M.E. (2006): Natural history of *Terrapene carolina* (Box Turtles) in an urbanized landscape. Southeast. Nat. **5**: 191-204.

Burton, T.M., Likens, G.E. (1975): Salamander populations and biomass in Hubbard Brook Experimental Forest, New Hampshire. Copeia **1975**: 541-546.

Bury, R.B. (2006): Natural history, field ecology, conservation biology and wildlife management: Time to connect the dots. Herpetol. Conserv. Biol. **1**: 56-61.

Campbell, C.E., Warkentin, I.G., Powell, K.G. (2004): Factors influencing the distribution and potential spread of introduced anurans in western Newfoundland. Northeast. Nat. **11**: 151-162.

Converse, S.J., Iverson, J.B., Savidge, J.A. (2005): Demographics of an ornate box turtle population experiencing minimal human-induced disturbances. Ecol. Appl. **15**: 2171-2179.

DePari, J.A. (1996): Overwintering in the nest chamber by hatchling Painted Turtles, *Chrysemys picta*, in northern New Jersey. Chelonian Conserv. Biol. **2**: 5-12.

Flato, G.M., Boer, G.J. (2001): Warming asymmetry in climate change simulations. Geophys. Res. Lett. **28**: 195-198.

Frazer, N.B., Gibbons, J.W., Greene, J.L. (1991): Growth, survivorship and longevity of Painted Turtles *Chrysemys picta* in a Southwestern Michigan Marsh. Am. Midl. Nat. **125**: 245-258.

Germano, D.J. (1993): Shell morphology of North American tortoises. Am. Midl. Nat. **129**: 319-335.

Germano, D.J., Bury, R.B. (1998): Age determination in turtles: evidence of annual deposition of scute rings. Chelonian Conserv. Biol. **3**: 108-109.

Gibbons, J.W., Scott, D.E., Ryan, T.J., Buhlmann, K.A., Tuberville, T.D., Metts, B.S., Greene, J.L., Mills, T., Leiden, Y., Poppy, S., Winne, C.T. (2000): The global decline of reptiles, Déjà vu Amphibians. BioScience **50**: 653-666.

Gibbs, J.P., Breisch, A.R. (2001): Climate warming and calling phenology of frogs near Ithaca, New York, 1900-1999. Conserv. Biol. **15**: 1175-1178.

Green, D.M., Root, T.L., Kiesecker, J.M. (2001): Amphibian breeding and climate change. Conserv. Biol. **15**: 1804-1809.

Hairston Jr., N.G., Walton, W.E. (1986): Rapid evolution of a life history trait. Proc. Natl. Acad. Sci. **83**: 4831-4833.

Huey, R.B., Gilchrist, G.W., Carlson, M.L., Berrigan, D., Serra, L. (2000): Rapid evolution of a geographic cline in size in an introduced fly. Science **287**: 308-309.

Janzen, F.J. (1994): Climate change and temperature-dependent sex determination in reptiles. Proc. Natl. Acad. Sci. USA. **91**: 7487-7490.

Kipp, R.L. (2003): Nesting ecology of the eastern box turtle (*Terrapene carolina carolina*) in a fragmented landscape. Unpublished Masters thesis, University of Delaware, Newark, Delaware, USA.

Kristensen, D.M., Jorgensen, T.R., Larsen, R.K., Forchhammer, M.C., Christoffersen, K.S. (2006): Inter-annual growth of Arctic Charr (*Salvelinus alpinus*, L.) in relation to climate variation. BMC Ecology **6**: 85-93.

LaBaugh, J.W., Winter, T.C., Swanson, G.A., Rosenberry, D.O., Nelson, R.D., Euliss Jr., N.H. (1996): Changes in atmospheric circulation patterns affect mid-continent wetlands sensitive to climate. Limnol. Oceanogr. **41**: 864-870.

Madden, R.C. (1975): Home range, movements, and orientation in the Eastern Box Turtle, *Terrapene carolina carolina*. Dissertation, The City University of New York, New York, U.S.A.

Martinez-Meyer, E. (2005): Climate change and biodiversity: Some considerations in forecasting shifts in species' potential distributions. Biodiversity Informatics **2**: 42-55.

McCallum, M.L. (2007): Amphibian decline or extinction: Current declines dwarf background extinction rate. J. Herpetol. **41**: 483-491.

McCallum, M.L., McCallum, J.L. (2006): Publication trends of natural history and field studies in herpetology. Herpetol. Conserv. Biol. **1**: 62-67.

Meyers, L.S. (1996): Environmental services of biodiversity. Ecology **93**: 2764-2769.

Neter, J., Kutner, M.H., Nachtsheim, C.J., Wasserman, W. (1996): Applied Linear Models, 4th Edition. St. Louis, McGraw-Hill.

Nichols, J.T. (1939): Data on size, growth and age in the Box Turtle, *Terrapene carolina*. Copeia **1939**: 14-20.

NOAA (National Oceanic and Atmospheric Association) (2000): U.S. Climate at a Glance. Available at http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html.

Parmesan, C. (2006): Ecological and evolutionary responses to recent climate change. Ann. Rev. Ecol. Syst. **37**: 637-669.

Parmesan, C., Root, T.L., Willig, M.R. (2000): Impacts of extreme weather and climate on terrestrial biota. Bulletin of the American Meteorological Society **81**: 443-450.

Piha, H., Luoto, M., Piha, M., Merila, J. (2007): Anuran abundance and persistence in agricultural landscapes during a climatic extreme. Glob. Chang. Biol. **13**: 300-311.

Plummer, M.V. (2006): Nest emergence of Smooth Softshell Turtle (*Apalone mutica*) hatchlings. Herpetol. Conserv. Biol. **2**: 61-64.

Pounds, J.A., Crump, M.L. (1994): Amphibian declines and climate disturbance: the case of the Golden Toad and the Harlequin Frog. Conserv. Biol. **8**: 72-85.

Pounds, J.A., Fogden, M.P., Campbell, J.H. (1999): Biological response to climate change on a tropical mountain. Nature **398**: 611-615.

Pounds, J.A., Bustamante, M.R., Coloma, L.A., Cosuegra, J.A., Fogden, P.L., Foster, P.N., La Marca, E., Masters, K., Merino-Viteri, L.A., Puschendorf, R., Santiago, S.R., Sanchez-Azofeifa, G.A., Still, C.J., Young, B.E. (2006): Widespread amphibian extinctions from epidemic disease driven by global warming. Nature **439**: 161-167.

Rahel, F.J., Keleher, C.J., Anderson, J.L. (1996): Potential habitat loss and population fragmentation for cold water fish in the North Platte River Drainage of the Rocky Mountains: Response to climate warming. Limnol. Oceanogr. **41**: 1116-1123.

Schlaepfer, F., Schmid, B., Seidl, L. (1999): Expert estimates about effects of biodiversity on ecosystem processes and services. Oikos **84**: 346-351.

Seimon, T.A., Seimon, A., Daszak, P., Halloys, S.R.P., Schloegel, L.M., Aguilar, C.A., Sowell, P., Hyatt, A.D., Konecky, B., Simmons, J.E. (2007): Upward range extension of Andean anurans and chytridiomycosis to extreme elevations in response to tropical deglaciation. Glob. Chang. Biol. **13**: 288-299.

Silvert, W. (1997): Ecological impact classification with fuzzy sets. Ecol. Model. **96**: 1-10.

Simons, A.M. (2002): The continuity of microevolution and macroevolution. J. Evol. Biol. **15**: 688-701.

Taheri, S.M. (2003): Trends in fuzzy statistics. Aust. J. Stat. **32**: 239-257.

Thompson, J.N. (1998): Rapid evolution as an ecological process. Trends Ecol. Evol. **13**: 329-332.

Tucker, J.K., Maher, R.J., Theiling, C.H. (1995): Year-to-year variation in growth in the red-eared turtle, *Trachemys scripta elegans*. Herpetologica **1995**: 354-358.

U.S. EPA (1998): Climate change and Arkansas. Office of Policy, Planning and Evaluation. EPA 236-F-98-007d.

Walde, A.D., Bider, J.R., Masse, D., Saumure, R.A., Titman, R.D. (2007): Nesting ecology and hatching success of the Wood Turtle, *Glyptemys insculpta*, in Quebec. Herpetol. Conserv. Biol. **2**: 49-60.

Wilson, D.S., Tracy, C.R., Tracy, C.R. (2003): Estimating age of turtles form growth rings: a critical evaluation of the technique. Herpetologica **59**: 178-194.

Zug, H.R., Vitt, L.J., Caldwell, J.P. (2001): Herpetology: An introductory biology of Amphibians and Reptiles, 2nd Edition. San Diego, Academic Press.

Received: June 22, 2007. Accepted: January 10, 2009.