Population viability analysis and effect of conservation measures in *Emys orbicularis* in Northeast Germany using computer simulation

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The European pond turtle (*Emys orbicularis*) is endangered and protected in Germany. Native relict populations with at most 10–15 individuals per population occur in the northeast of the country. As Germany is part of the species’ natural range, adaptations to the temperate climate are likely. An object-oriented simulation model (*Emys*-I) was created to reveal the most sensitive parameters in population biology of German pond turtles. During the simulation, mortality of adults and older juveniles had to be very low to ensure population stability. Nest numbers and hatching success had to be sufficient for population recruitment; this seems to be the case under natural conditions. Population stability was also significantly influenced by the sex ratio. However, due to unknown long-term effects the sex ratio should not be manipulated for conservation purposes. Conservation measures for increasing individual numbers were modelled for a wild population. A combination of nest protection and headstarting for two years proved to be most successful; nest protection alone could not ensure sufficient population growth. Conservation measures are recommended to be performed over at last 20 years to produce stable populations and have to be accompanied by a monitoring programme to compare population development and model predictions.

Key words: *Emys orbicularis*, simulation model, population viability analysis (PVA), minimum population size (MVP), conservation, Germany.

Introduction

The European pond turtle *Emys orbicularis* (L., 1758) is an endangered and protected species in Germany and in many other parts of its range. The last native German populations occur in the northeast of the country. Genetic studies (LENK et al., 1998; POSCHADEL, 2003) and morphological characteristics according to FRITZ (1992) verified their autochthonous status (SCHNEEWEISS, 2003; PAUL, 2004). Populations are very small with estimated maximum numbers of 10 to 15 individuals each (FRITZ & GÜNTER, 1996; SCHNEEWEISS, 2003). The present situation is due to habitat alteration and former overexploitation for food. Turtle mortality on roads and in fishtraps further contributed to the decline (SCHNEEWEISS, 1997; SCHNEEWEISS & FRITZ, 2000).

Northern *E. orbicularis* populations seem to be well adapted to a temperate climate by their long life span (ROLLINAT, 1934; JABŁOŃSKI & JABŁOŃSKA, 1998), low adult mortality (PAUL,
2004; Mitrus, pers. comm.), and the production of large clutches (Keller, 1999). However, low population densities increase extinction risk due to stochastic events or catastrophes which may amplify each other (Shaffer, 1981; Gilpin & Soule, 1986). An interaction of the above-mentioned factors and small population size, combined with reproductive constraints of temperate climate, are likely to prevent the recovery of German *E. orbicularis* populations without effective conservation measures.

In Northeast Germany, the habitats of *E. orbicularis* are wetlands close to xerothermic sites. Both are protected landscape types in Germany. Moreover, European pond turtles and their habitats are also protected by EU law (92/43/EG). Hence, *E. orbicularis* has the potential of a ‘target species’ to protect landscape and many other endangered species of fauna and flora. To determine the most important conservation measures for *E. orbicularis* in Northeast Germany, I analyzed: (i) whether changes in certain population parameters affect minimum viable population size (MVP; Shaffer, 1981); and (ii) which conservation measures support the greatest population growth to a self-sustaining size.

Ideally, a long-term study would be the best way to answer these questions. However, long-term studies are rare due to the long life span of freshwater turtles (Gibbons, 1990) and a lack of funding. Computer simulations are a powerful tool to investigate the impact of certain conservation measures on population growth prior to implementation (Lacy, 1993/94). Thus, I decided to use a computer simulation for performing a restricted population viability analysis (FVA: Gilpin & Soule, 1986). However, it has to be kept in mind that results of a computer simulation depend on model constraints and quality of input data.

**Material and methods**

The object-oriented simulation model *Emys-I* was written in Object Pascal using the program Borland Delphi 4.0. It covers the aspects mortality, reproduction, and mean climatic impact on reproductive success. Direct habitat impact was not considered. The program code is given in Paul (2004).

*Emys-I* has certain underlying assumptions. Some derive from climatic conditions, natural history and behaviour of *Emys orbicularis* in Northeast Germany. Others had to be set due to model constraints or a lack of data about certain natural history aspects. Assumptions are listed (with comments) as follow: (1) all hatchlings overwinter in the nest chamber (Andreas et al., 1996; Schneeweiss, 2003); (2) at least one male is needed for reproduction (no sufficient data how many females can be fertilized by one male, about mating system, or sperm competition); (3) no immigration or emigration occurs (lack of data; no information about differences between sexes and age classes); (4) a turtle reaches a maximum age of 150 years (probably overestimated: age records are 88 or 98 years, and 120 years; Rollinat, 1934; Jabłoński & Jabłońska, 1998); (5) males mature at 10, females at 12 years (rough estimate according to Fritz & Günther 1996; Schneeweiss 2003; Mitrus, pers. comm.); (6) time steps during simulation are annual and start in winter; (7) turtles of the initial population have an age of 35 years for adults and of 5 years for juveniles (age determination in adults is difficult; data for juveniles lacking); (8) if the number of males, females, or juveniles (including overwintering hatchlings, *juv_age0*) exceeds 10,000, the simulation is interrupted and the actual population size is used for the output (set to prevent too long simulation times as there is no data about habitat capacity and regulation mechanisms); (9) overwintering hatchlings (*juv_age0*) are not used for calcu-
lating population size (also not counted in field research).

Due to the long generation cycle, the simulation time was set at 1,000 years to cover about 100 generations. To translate biological information into program text, several main-procedures (Fig. 1) and subprocedures (Fig. 2) are used.

Decisions in Emys-I are based on probabilities. The object-oriented modelling is close to nature as turtles constitute the objects. Empiric field data can be used directly and the model is easily understood by biologists. For example, Emys-I calculates whether a certain adult male survives the simulation year. The probability for its death is 0.02 (p\textsubscript{mortmale}), originating from the mean adult survival probability of 0.98 in Central Poland (Mitrus, pers. comm.). To calculate the survival probability of the virtual male, Emys-I creates a random number ≥ 0 and < 1. The male dies if the number is below 0.02 and survives if it is 0.02 or more.

For calculations in Emys-I, data were used as subparameters. For a better understanding, some subparameters were combined in thematic groups (main-parameters). In the following, the parameters are described and their biological background is explained:

(1) **Nesting:** existence and survival probability (p) of a nest and p of appropriate climatic conditions for egg-development, hatching, and successful hatching overwintering in the nest:

\[
\text{nesting} = p_{\text{nesting}} \cdot (1 - p_{\text{mortclutchpred}}) \cdot (1 - p_{\text{mortclutchsummer}}) / (1 - p_{\text{mortclutchwinter}})
\]

\(p_{\text{nesting}}\): p of a female to oviposit during the simulation year; \(p_{\text{mortclutchpred}}\): p of a nest to be destroyed by predators; \(p_{\text{mortclutchsummer}}\): p of summer conditions preventing embryonic development; \(p_{\text{mortclutchwinter}}\): p of winter temperatures killing hatchlings during hibernation in the nest).

(II) **Hatching:** p of hatching of a juvenile (values are calculated from incubator data as climatic impact is already part of parameter nesting):

\[
hatching = p_{\text{eggfert}} \ast p_{\text{egghatch}}
\]

\(p_{\text{eggfert}}\): p of each egg to be fertilized; \(p_{\text{egghatch}}\): hatching p.

(III) **Adultmort:** p of an adult male or female to die within the simulation year:

\[
\text{adultmort} = p_{\text{mortmale}} = p_{\text{mortfem}}
\]

(IV) **Mortjuv 1\textsuperscript{st} year:** p of a juvenile to die during the first year of life:

\[
\text{Mortjuv 1}\textsuperscript{st} \text{year} = p_{\text{mortjuvnestmigration}} \ast p_{\text{mortjuvwinter}}
\]

\(p_{\text{mortjuvnestmigration}}\): p of a juvenile to die during migration from the nest to the water; \(p_{\text{mortjuvwinter}}\): p of a juvenile to die during the remaining time of its first year.

(V) **Mortjuv 2\textsuperscript{nd} year:** p of a juvenile to die during its second year:

\[
\text{Mortjuv 2}\textsuperscript{nd} \text{year} = p_{\text{Mortjuv2}}
\]

(VI) **Mortjuvster:** p of a juvenile to die between its third year and maturity:

\[
\text{Mortjuvster} = p_{\text{mortjuvster}}
\]

(VII) **Males at birth:** p of a hatching to be male:

\[
males \text{ at birth} = p_{\text{sexratio}}
\]

(Note that hatching and adult sex ratio differ due to the two years divergence between males and females in maturity).

(VIII) **Population size:** population size at the beginning of each replicate.

(IX) **Clutchsize:**

For females < 40 years: \(calc_n_{\text{egg}} = \text{round}(14.6 + (\text{random} - 0.5) \ast 2.0 \ast 2.7)\)

For females ≥ 40 years: \(calc_n_{\text{egg}} = \text{round}(8.3 + \text{random} \ast 3.0)\)

Fig. 2. Subprocedures of Emys-I (reproduction, mortmale, and maturity): most decisions are based on probabilities. Subprocedures mortfem and mortjuv work according to mortmale.
Table 1. Data source for subparameter values and assumptions of Emys-I and resulting parameter values. For main-parameter calculation see text. Asterisked values are calculated from literature data.

<table>
<thead>
<tr>
<th>Assumptions or main-parameters</th>
<th>Values or subparameters with values</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clutch size</strong></td>
<td>&lt; 40 years: 14.63 (2.86)</td>
<td>Northeast Germany (study site; SCHNEEWEB, 2003)</td>
</tr>
<tr>
<td></td>
<td>≥ 40 years: 8.3 (2.0)</td>
<td><strong>Clutch size</strong></td>
</tr>
<tr>
<td>Adult sex ratio</td>
<td>0.38 male : 1 female</td>
<td>Northeast Germany (study site; PAUL, 2004)</td>
</tr>
<tr>
<td>Percentage juveniles</td>
<td>15%</td>
<td>Central France (SERVAN, 1998)</td>
</tr>
<tr>
<td>Reproductive period</td>
<td>For females at least up to the</td>
<td>East Poland (JABLOŃSKI &amp; JABŁOŃSKA, 1998), Central France (ROLLINAT, 1934)</td>
</tr>
<tr>
<td>Nesting 0.11</td>
<td>p_mortnesting 0.90</td>
<td>Northeast Germany (study site; PAUL, 2004)</td>
</tr>
<tr>
<td></td>
<td>p_mortclutchpred 0.56</td>
<td>Danube meadows, Austria (RÖSSLER, 2000)</td>
</tr>
<tr>
<td></td>
<td>p_mortclutchsummer 0.33*</td>
<td>Northeast Germany (SCHNEEWEB, 2003)</td>
</tr>
<tr>
<td></td>
<td>p_mortclutchwinter 0.60*</td>
<td>Northeast Germany (SCHNEEWEB, 2003)</td>
</tr>
<tr>
<td>Hatching 0.67</td>
<td>p_eggfert 0.72*</td>
<td>Northeast Germany (artificial incubation; **)</td>
</tr>
<tr>
<td>Adultmort 0.02</td>
<td>p_mortmale and p_mortfem 0.02</td>
<td>Central Poland (MITRUS, pers. comm.)</td>
</tr>
<tr>
<td>Mortjuv1st year –</td>
<td>p_mortjuvnestmigration</td>
<td>–</td>
</tr>
<tr>
<td>Mortjuv2nd year 0.5</td>
<td>p_mortjuv2 0.5</td>
<td>Central Poland (MITRUS, unpubl. data)</td>
</tr>
<tr>
<td>Mortjuvlater 0.1</td>
<td>p_mortjuvlater 0.1</td>
<td>Central Poland (MITRUS, unpubl. data)</td>
</tr>
<tr>
<td>Males at birth 0.4</td>
<td>p_sexratio 0.4</td>
<td>Calculated with Emys-I</td>
</tr>
</tbody>
</table>

**SCHNEEWEB, pers. comm.**

.*(random – 0.5) + 2.0 + 2.0*

The probabilities are drawn from mean values of field data (Fig. 1). As much empiric data as possible were included from a local population (PAUL, 2004) and of other native *E. orbicularis* populations in Northeast Germany. If no data were available, most similar populations (concerning subspecies and climatic conditions) were used to fill the gaps. Data sources, probabilities for each main-parameter, and underlying subparameters are summarized in Table 1. Test runs were performed to check the results on their biological plausibility. Mistakes have been corrected before running the analysis.

Impact of parameters on population survival (population viability analysis, PVA)

To investigate the impact of parameters on the minimum viable population size (MVP), the start population size was increased from the first value in 20 steps. rMVP was defined as the relative population size where the population has a minimum survival probability of 0.9 for the simulation time of 1,000 years. It is important to note that MVP might differ considerably even between closely related populations, due to different environmental constraints (SOULE, 1987).

In addition to varying the starting population size, the individual parameters were subsequently changed from 0 to 1 in 0.05 steps. Adultmort and mortjuvlater turned out to be very sensitive between 0 and 0.15. Therefore, they were varied in 0.005 steps.

Population survival probability (*survival*) was estimated from 100 replicates of the same parameter combination:

\[ \text{survival} = \text{number of extinct populations} / \text{number of all populations} \]

Efficiency of conservation measures

This aspect was investigated using the estimated population size of the studied local population (3 males, 8 females; PAUL, 2004) as a virtual starting population. Useful and applicable possible conservation measures in this population concern the parameters *nesting*, *mortjuv 1*st year*, and *mortjuv 2*nd year*. Three different combinations of conservation measures were tested:

(a) Protecting nests by smell-camouflaging with *Eau de Cologne* to reduce predation probabilities A: \( p_{\text{mortnestpredation}} = 0.3 \) and B: \( p_{\text{mortnestpredation}} = 0.1 \).

(b) Measure (a) plus artificial incubation of eggs to reduction mortality due to unfavourable climatic conditions and to reduce \( p_{\text{mortclutchsummer}} (0.2) \) and \( p_{\text{mortclutchwinter}} (0.4) \); release of headstarted juveniles into the water during the following summer to reduce nest migration mortality (\( p_{\text{mortjuvnestmigration}} \)) and mortality during the rest of the first year of life (\( p_{\text{mortjuv}} \)). For both no field data are available. The possible maximum value of *mortjuv 1*st year due to headstarting is 0.7.

(c) Measure (b) but juveniles are released during their third year of life to reduce mortality during their second year (\( p_{\text{mortjuv2}} = 0.3 \)). The possible maximum value of *mortjuv 2*nd year due to headstarting is 0.7.

As in reality not all nests can be covered with these measures, two probabilities were run, as described under (a). Simulation time was 25 years to investigate the impact on population growth.
Results

Impact of parameters on population survival (PVA)

In Figures 3–7 it is evident how changing parameter values impact the relative minimum viable population (rMVP). Three different scenarios (0.7, 0.8, 0.9) were used for juvenile mortality during the first year of life (mortjuv 1st year) as there were no sufficient field data for determining this parameter exactly. Figure 3 depicts the influence of mortjuv 1st year on population survival. No rMVP exists within the tested range when mortjuv 1st year exceeds values above 0.75. But if it is lower, rMVP is small.

Mortality of adults (adultmort) has to be very low to ensure population survival. The same is true for juvenile mortality from the third year of life to maturity (mortjuvlater), although this value can be a little bit higher (Fig. 4). The higher mortality during the first year (mortjuv 1st year) the lower values of adultmort and mortjuvlater, or higher rMVP, are required to ensure population survival.

Mortality of juveniles during their second year of life (mortjuv 2nd year, Fig. 5) has to be lower than mortjuv 1st year. No rMVP exists when mortjuv 1st year is 0.9. The rMVP decreases with lower mortjuv 2nd year as well as with lower mortjuv 1st year values.

The parameters nesting (existence and survival probability of a nest) and hatching (embryonic development and hatching) lower the rMVP size when increased (Fig. 6). An increase of these parameters allows higher mortjuv 1st year values.

The quota of males at birth impacts much rMVP (Fig. 7). Values above 0.5 do not support a

Fig. 3. Possible values for juvenile mortality during the first year of life (mortjuv 1st year) ensuring population survival under assumptions of Emsys=1.

Fig. 4. Impact of adult mortality (adultmort) and mortality of older juveniles (mortjuvlater) on rMVP. Simulations with mortjuv 1st year values 0.7 (+), 0.8 (x), and 0.9 (o). Note smaller scale of parameter axis compared with other figures. Arrows: values estimated from field data (Tab. 1).
of all few males dying from stochastic events. This part of the graph is not shown, since the model assumption that one male enables reproduction of all females allows no adequate prediction for very low male quota.

**Efficiency of conservation measures**

The parameters *nesting*, *hatching*, *mortjuv 1st year* and *mortjuv 2nd year* can be managed in the study population. The most effective population growth was obtained with a combination of all measures. The population growth could be further increased if a higher number of nests are protected against predation (Fig. 8). An effect of conservation measures on adult number, and therefore on the stable increase of population size in long-term view, turns out from 10 years onwards.

**Discussion**

**Computer simulations**

Simulations with Emys-I demonstrated an increasing parameter sensitivity concerning mortality from juvenile to adult age classes. This agrees with theoretical predictions from Congdon & Gibbons (1990) that life history strategies of turtles include longevity with a prolonged reproductive phase to compensate losses due to unfavourable years, high nest predation, or juvenile mortality. In Northeast Germany, *Emys orbicularis* repro-
Fig. 7. Impact of male quota at birth (males at birth) on rMVP size. In the lower part, no prediction is possible due to model constraints. Two different simulations resulted in rMVP sizes within the tested range: 
mortjuv 1st year values 0.7 (+) and 0.8 (×). Arrow: value estimated from field data (Tab. 1).

produce successfully only if warm summers, enabling embryonic development, are followed by winters with temperatures not dropping below −6°C in the nesting chamber (SCHNEEWEISS, 2003). These climatic requirements result in a reduced average annual reproductive output.

According to CONGDON & GIBBONS (1990), reproductive success can be increased by several strategies, like regular (annual) production of clutches, multiple clutches per season, or increase of clutch size (egg number). It is likely that most females reproduce annually in Northeast Germany. Eight females were found to be gravid during 32 of 33 recorded nesting migrations over eight years, leading to the estimate that 97% of females reproduce annually (PAUL, 2004). However, a second clutch is laid only very rarely. It could be only successful if an extremely warm spring allows very early oviposition. In my study population, only one case of a second clutch was recorded over eight years. It was of the same size as the first clutch and still laid during the normal nesting period. This second clutch could have developed successfully if climatic conditions would have been more favourable after spring (PAUL, 2004).

For nesting the assessed value of 0.1 might be too conservative. It originates from field data from six years with two unusually cold winters.

However, climatic data indicate that nesting is likely to be about 0.2 or more in long-term average (SCHNEEWEISS, 2003).

Body size and clutch size of turtles are significantly correlated (GIBBONS & GREENE, 1990). The largest carapace lengths for E. orbicularis are known from the northern distribution area (FRITZ, 2001). Northeast German E. orbicularis lay up to 21 eggs per clutch with a mean of 12.6 (SCHNEEWEISS, 2003). Adult mortality seems to be very low in northern populations with no human impact. In my study site, the observed maximum mortality was 0.016 (PAUL, 2004) and in Central Poland it is 0.02 (MITRUS, pers. comm.). This contrasts with the situation in warmer climates. There, turtles are smaller, have smaller clutches but produce more than one clutch per year (KELLER, 1999; FRITZ, 2001). However, in the south females do not necessarily nest each year, due to drought periods (KELLER, 1997; NAULLEAU, 1999). Also adult mortality could be higher there (KELLER, 1997 for Doñana, Southwest Spain) than in the north.

The life span of turtles may exceed long-term research projects. Thus, longevity and reproductive success are extremely difficult to assess. Computer simulations help to obtain data for future predictions. My simulation demonstrates that increasing mortality of adults and older juveniles leads to serious problems for population survival. Considering the high adult mortality due to the historical overexploitation of Northeast German and Polish populations for food (SCHNEEWEISS, 1997), their survival up to the present is surprising.

The computer simulation highlights that optimal nesting sites are required to ensure long-term survival of populations. Nest predation and mortality of early juvenile stages may be less important when population size is high (without knowing its absolute size) and adult mortality is close to zero. In agreement with MITRUS & ZEMANEK (2004), the computer simulation demonstrates that every conservation effort fails if these prerequisites are not met. In my research population, on which the presented computer simulation was mainly based, a low mortality of older turtles seems to be the given state.

Further recommended conservation measures
Due to the complicated sex determination mechanism in turtles, sex ratio manipulation should be not used for increasing population growth according to GHRONDOT et al. (1998). These authors recommend protecting nests under natural condi-
Fig. 8. Impact of three conservation measures on population growth in *Emys orbicularis*. Top: measure (a) smell-camouflaging of nests to reduce predation; centre: measure (b) = measure (a) plus artificial incubation and headstarting during the first year of life; bottom: measure (c) = measure (b) plus headstarting for the second year of life. All measures were simulated in two intensities (A and B). For further explanations see text.
tions against predation. This type of conservation is practiced by MITRUS (pers. comm.) in Central Poland, combined with headstarting hatchlings over the first winter. Northeast German populations are smaller and the climatic conditions allow successful reproduction in fewer years than in the more continental climate of Poland. Therefore, northeast German *E. orbicularis* populations are likely to be lost within the next few decades without support. Hence, eggs should be incubated artificially, imitating a favourable natural temperature regime.

In the computer simulation, the most effective population growth was achieved if all possible measures were combined. Therefore, as many nests as possible should be camouflaged with ‘Eau de Cologne’ to avoid predation. Moreover, as many eggs as possible should be incubated artificially to minimize losses due to unfavourable climatic conditions. Young turtles should be head-started under conditions most similar to nature. The ‘Species Protection Programme for turtles and their ability to search for food. The started juveniles maintain their natural flight response and their ability to search for food. The ‘Species Protection Programme for *Emys orbicularis*’ in Brandenburg fulfils all these requirements (SCHNEEWEISS, 1995) and thus contributes considerably to securing the species’ future there.

Released juveniles have to be marked permanently to distinguish them from individuals hatched in nature. A monitoring programme to investigate the results and to allow comparing real population development with predictions made by Emys-I in this study should accompany these measures in future. Conservation measures in Brandenburg should be conducted for at least 20 years to establish a stable population size (cf. CONGDON et al., 1993). We have still no idea about natural population densities of Northeast German *E. orbicularis*. The habitat is optimal and food does not appear to be the limiting factor (PAUL, 1997, 2004). Thus, the habitat capacity surely allows for a distinctly higher individual density. Moreover, turtles can emigrate to reach many other suitable water bodies which are currently not inhabited by *E. orbicularis*.

A comparison of reproduction strategies of *E. orbicularis* from different parts of the range is a future challenge. Modification of Emys-I could be an option to investigate geographic variation in life history traits. The model code of Emys-I was published in PAUL (2004) and is open for public application.

Acknowledgements

I wish to thank J. PARZEFALL for advising my PhD, the members of the Ecological Station Fabriksschleichelach, in particular O. MITTesser, for pushing my knowledge of modelling to exponential growth, C. KELLER and B. WUNTKE for fruitful discussions, the members of the Ethological Department of the University of Hamburg for equipment, working space, and support in many ways, N. SCHNEEWEISS and S. MITRUS for discussions and providing unpublished data, K. HEUBEL, A. KERN and F. THOMSEN for correcting an earlier draft of the manuscript, and everyone who supported my fieldwork personally or logistically. My PhD has profited from a grant of Deutsche Bundesstiftung Umwelt (DBU). My parents provided final financial support.

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