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Using fuzzy systems to simulate population dynamics of Mediterranean arthropods

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ABSTRACT: An age-structured model involving demographic parameters is used to simulate population dynamics of Mediterranean arthropods. For parameter estimation a fuzzy set system is employed. Large white noise in autumn and spring superimposed on sinusoidal varying temperature drives stochastic equilibria in population size. The interplay among life history traits of populations at equilibrium is discussed.

1 INTRODUCTION

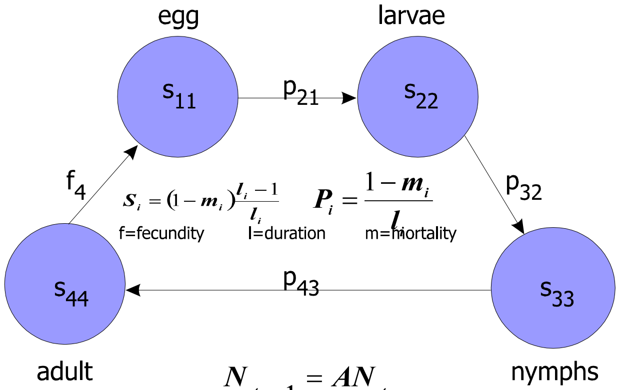
Research on the phenology of arthropods from Mediterranean regions reveal synchronization of population size with the mid- and long-term oscillations in the environmental variables displaying either right or left skewing phenologies (e.g. Radea 1989, Asikidis and Stamou 1991). Stamou et al. (2004) suggested that such phenologies are dictated by oscillating external climatic forces and more specifically temperature. Stamou (1998) ascribed adaptive values to different metabolic and life history traits of these animals, whereas, Stamou et al. (2004) employed an age-structured model involving demographic parameters (Spencer & McGee 2001; McGee and Spencer 2001; Oli and Zinner 2001) and described mechanisms underlying such phenologies.

However, due to imprecise and/or limited data, indirect measurements etc. (Mpimpas et al. 2001), numerical simulations of these models provide vague approximations to census data (Jensen and Miller 2001). Specifically, in Mediterranean habitats consisted of fine-grained mosaics of more or less isolated microsites (Stamou 1998) this uncertainty arises from spatial and temporal randomness and is different than that accounted for by stochastic models. To formalize this kind of uncertainty in this paper we employ a fuzzy systems approaches (Bult and van Kooten 2001).

2 MODELLISATION

In this paper we employed a Leslie-type, life stage-structured model (Caswell 1989) and performed weekly numerical simulations. A life cycle including 4 life stages is considered. In Fig.1 model formulation and estimations employing demographic parameters are shown. Moreover, demographic vectors and the transition matrix are also shown.

To estimate demographic rates a fuzzy system is used. The claim that words, especially adjectives, are ambiguous and that the truth of a linguistic variable is a matter of degree are starting points for fuzzy systems theory (Terano et al. 1992). The advantage of fuzzy systems stems from the fact that instead of arithmetic they involve linguistic variables. Linguistic variables (e.g. *very low temperature*, *high temperature* and the like, are potentially rich in value (Stamou and Stamou 1996).



$$S_i = (1 - m_i)\frac{l_i - 1}{l_i} \qquad P_i = \frac{1 - m_i}{l_i}$$

$$N_{t+1} = AN_t$$

$$N_t = \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{bmatrix} \qquad A = \begin{bmatrix} S_1 & 0 & 0 & f_1 \\ P_1 & S_2 & 0 & 0 \\ 0 & P_2 & S_3 & 0 \\ 0 & 0 & P_3 & S_4 \end{bmatrix}$$

Figure 1. A four-life stage cycle of arthropods. The population dynamics model $N_{t+1}=A*N_t$, The form of the demographic vector N_t and of the transition matrix A, as well as estimation of the matrix elements S_i and P_i employing demographic parameters are also shown.

3 THE STRUCTURE OF THE FUZZY SYSTEM

Fuzzy logic comes to expand the traditional set theory. Suppose that we want to build a simple model describing changes in fecundity as a function of temperature. It is positive that even in the simplest case this function is quite complex, while in order to factualise this issue the required experiments and statistical treatments render the situation even more complex and time consuming. However, any expert could say what happens to fecundity whenever temperature is, for example, medium. In order to formalise these situations the model should accept expertise expressed in a natural language. This technique was used in traditional expert systems. Nevertheless, the definition of the linguistic variables as parts of a “*universe of discourse*” (e.g. the temperature gradient: *very low*, *low*, *relatively low*, *medium*, *relatively high*, *high*, *very high* temperatures) is problematic. Indeed, in a traditional set (in fuzzy logic this is a crisp set), there is non-continuity to the transaction from one subset to another and an element either belongs or doesn’t belong to a set. For instance it is possible to put a temperature of 20 ^{0}C to the subset «*high*» and classify 20.1 ^{0}C to the subset «*very high*». By contrast, in a fuzzy set an element is always member of the set with a degree of membership from 0 to 1.

Any fuzzy system is made up of the Fuzzification compartment, the Fuzzy Knowledge Base element, the Fuzzy Inference Mechanism and the Defuzzification compartment (Fig. 2).

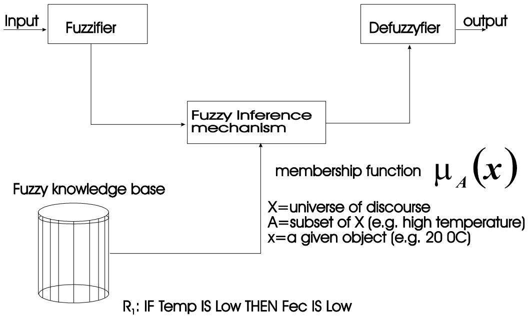
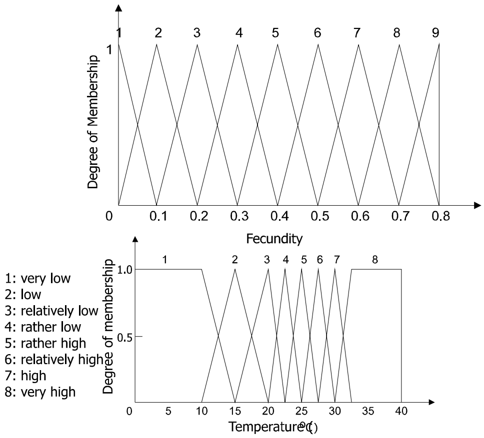


Figure 2. The structure of the fuzzy system



The membership function assigns
weights to any object

$$A(high\ temperature) = 0/0^oC + 0/10^oC + 0.3/20^oC + 1/40^oC$$

Figure 3. Definition of fuzzy sets on the variables *Fecundity* and *Temperature*.

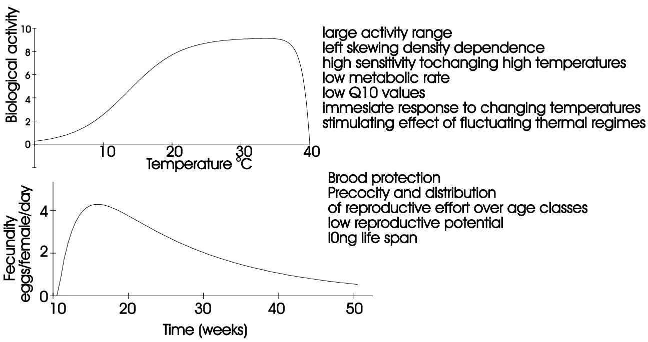


Figure 4. Temperature dependence of Biological activity and Fecundity.

Modeling grounds upon expertise shown in Fig. 3 and 4. It exemplifies ideas by Stamou (1998) distinguishing among temperate introvert arthropods and extrovert Mediterranean animals. In the former population regulation is mainly resulted from biotic constraints such as density dependence, inter-specific competition and the like. By contrast, abiotic factors such as humidity and temperature override regulation of population size in Mediterranean arthropods. Soil moisture has an on/off effect on arthropods survival and correlates mostly with the spatial distribution of animals among favorable and unfavorable microsites. Consequently, moisture effects are not taken into account. By contrast, the development of arthropods' life cycles strongly depends on spatially and temporarily varying temperature (Asikidis and Stamou 1991).

4 SIMULATION RESULTS

Under conditions of sinusoidal variation in temperature population expands (Fig. 5). It is remarkable that weak noise in temperature (±3 °C) superimposed on sinusoidal fluctuations does not affect population dynamics. By contrast, under more realistic Mediterranean conditions with large white noise (±10 °C) in autumn and spring and small white noise in summer and winter, numbers attain finally stochastic equilibrium. Sensitivity analysis for the population at equilibrium showed enhanced sensitivity of the rate of increase to changes in adult fecundity. Longevity and mortality of juveniles is of minor importance for changes in population growth rate.

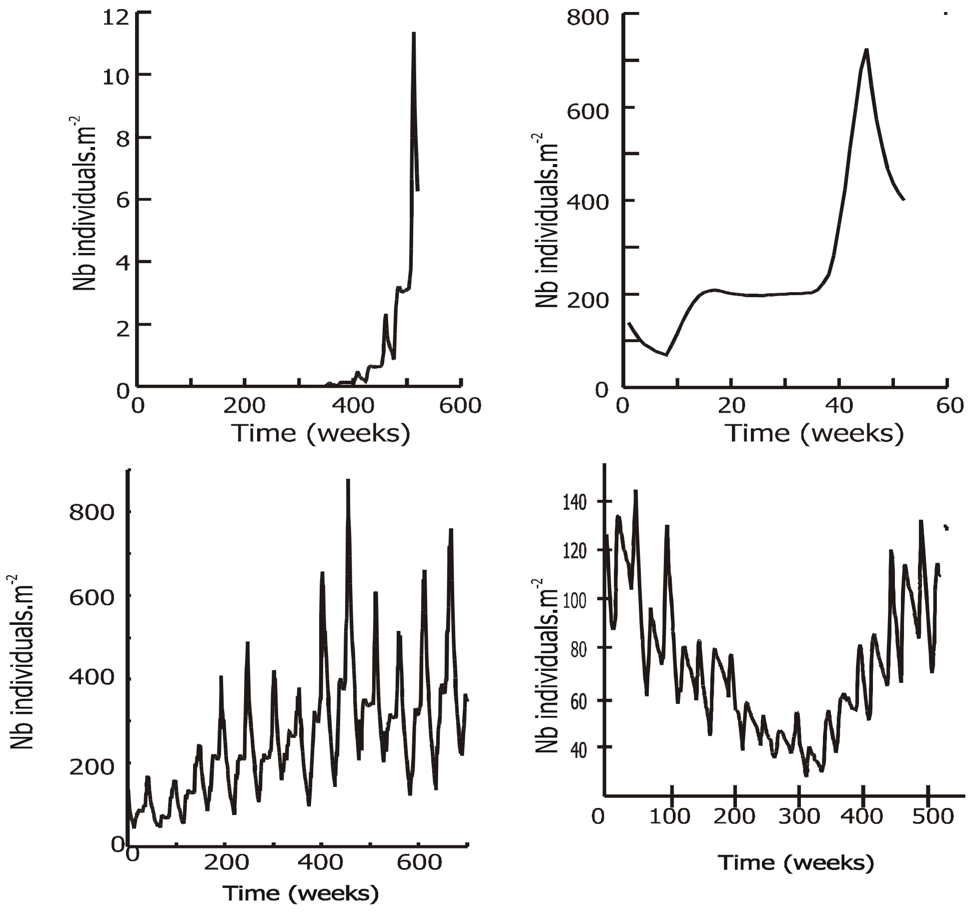


Figure 5. Simulation results. Upper left: interannual expansion, upper right: annual projection of population dynamics, bottom left: interannual stochastic equilibrium, bottom right: interannual recovery.

5 DISCUSSION

Employment of linguistic variables and rules not only simplified the studied system but also generated more realistic and general descriptions of the population dynamics of Mediterranean arthropods.

The model describes dynamics, which parallel seasonal fluctuations of climatic variables and display skewing phenologies reported by many authors (Stamou and Sgardelis 1989, Asikidis and Stamou 1991, Sgardelis et al. 1993).

Obviously, changing temperature forces population to follow the seasonality of the Mediterranean climate. Moreover, white noise in spring and autumn generates stochastic equilibrium. To explain these situations Stamou et al. (2004) stated that skewed seasonal phenologies are mainly driven by the immediate response of animals to seasonally varying temperature coupled with left skewing dependence of demographic parameters on temperature.

Life history tactics of arthropods from Mediterranean-type ecosystems are reviewed by Stamou (1998). A relevant discussion with regard to oribatid mites is given in Stamou et al. (1993). In the present paper to the life history of Mediterranean arthropods are assigned rather conservative traits, such as long lasting adulthood, ontogenetic cost put mainly on juveniles and reduced adult mortality. However, conformist characteristics such as relatively high reproductive rate, uneven distribution of reproductive effort, rapid development of juveniles into adult and precocity are also assigned to Mediterranean arthropods and it is in accordance with Stamou (1998). Matching of simulation data generated in this paper with census data substantiate these assumptions. Conservative characteristics appear adaptive for the persistence of animals in a harsh environment, while conformist characteristics force population size to conform to the seasonality of the Mediterranean climate.

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