Appendix 2. DemoViz model description (ODD)

The following model description complies with the ODD (Overview, Design concepts, and Details) protocol for standardized descriptions of individual-based and agent-based models (Grimm et al. 2006, 2010, 2020).

1 Purpose

The purpose of the DemoViz model is to create example visualizations of causation in a hypothetical SES. The hypothetical research purpose of the model could be to predict the effects of different pollution, fishing or climate scenarios on the dynamics of a river fish population and the catch from this population, and to understand causal mechanisms that lead to these dynamics.

2 Entities, state variables and scales

The model environment comprises a river of 60 km length and individuals belonging to a fish population within this river. The river is characterized by its state variables pollution level P, temperature T, and capacity C. P (unitless value between 100 and 200) and T (in °C) do not vary along the river, but change in time. The capacity C determines the maximum number of fish individuals that can live in the river. It changes in time too. Each fish individual is characterized by its state variables body condition B and location L along the river. Both B (unitless value between 0 and 1) and L (position between 0 and 60 km) change in time depending on the environmental conditions P and T (cf. 7 Submodels). Each time step represents one year. Simulations were run for 200 years.

3 Process overview and scheduling

Each time step includes the following processes: fish movement, fish reproduction, fish mortality, fishing. After fish movement, the remaining processes are scheduled synchronously. This means that new born individuals cannot die in the same time step. If both mortality and fishing happen to cause death of the same individual, the information is stored and at the end of the time step half of these death events are assigned to mortality and to fishing, respectively. The rationale for this is to approximate synchronous dynamics since the temporal order of events within one time step is not explicitly modeled.

4 Design concepts

Emergence. All process rules and the individuals' state variables' responses to environmental conditions are imposed. The population abundance and the fishing catch emerge from the interplay of all modeled processes.

Adaptation. Fishing is adaptive to the fish population abundance. Only if the abundance was above a certain threshold (here set to 150 individuals) in the previous time step, fishing is carried out (cf. 7 Submodels – Fishing).

Objectives. The objective of adaptive fishing is not to exert additional pressure on the fish population when it has a low abundance, thus reducing the risk of extinction.

Sensing. The model uses one overall temperature value for the whole river (cf. 2 Entities, state variables and scales). However, we assume that in reality the local temperature actually varies along the river, the individuals sense this local temperature and move to a location with their preferred temperature range. This is implicitly considered in a simple manner as the fish individuals change their location in response to the overall river temperature (cf. 7 Submodels – Fish movement).

Interaction. Fish individuals' competition for resources is modeled implicitly via limiting the maximum population abundance to the capacity of the river. Humans, who are not explicitly modeled, interact with the fish via altering the level of river pollution and via fishing.

Stochasticity. The creation of environmental input data contains stochastic elements. The individuals' state variable's responses to environmental conditions are partly stochastic. The model processes contain stochastic elements, i.e. random movement, random death and reproduction events, and random fishing mortality (cf. 7 Submodels). These stochastic elements represent variability that is potentially essential for the modeled dynamics, but without explicitly including the causes of this variability.

Observation. The fish population abundance and the fishing catch rate over time are the main observations. Each state variable of the individuals as well as emergent process variables (e.g. population mortality rate, population reproduction rate) can be observed (Fig. A2.1).

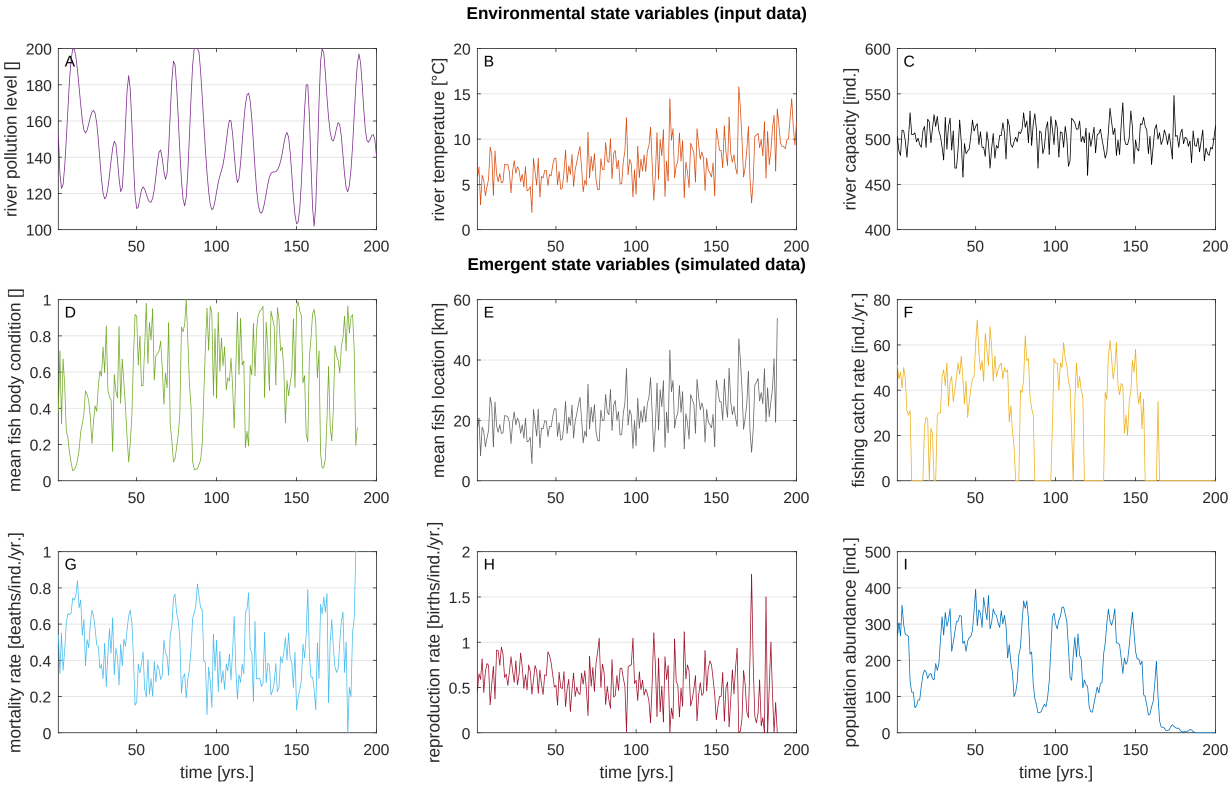

Fig. A2.1. Example time series from the DemoViz model for 200 years (X-axes). **A-C** Environmental state variables used as input data (cf. Y-axes for variable names and units). **D-I** Emergent state variables obtained in one stochastic simulation run with the model (cf. Y-axes for variable names and units). The mortality rate (G) refers to mortality apart from deaths due to fishing (F). In this example run, the fish population collapsed (went extinct) after 189 years (I).

5 Initialization

The fish population is initialized with 350 individuals. Their state variable values are not initialized separately as they depend on current environmental conditions in each time step and, thus, get assigned during the submodels Fish movement and Fish mortality (cf. 7 Submodels).

6 Input data

The model uses input data to represent time series of river pollution level, temperature and capacity over the simulation time of 200 years (Fig. A2.1A-C). These hypothetical input data were randomly generated to represent reasonable variability in the environmental conditions.

7 Submodels

Fish movement. Changes in river temperature T cause the fish to change their locations. The rationale for this relationship is that we assume that the real temperature varies along the river (decreasing from position 0 to position 60 km). This means that when the whole river gets warmer (colder), areas with the temperature range preferred by the fish shift to higher (lower) positions along the river. We additionally assumed that these areas get larger when the overall river temperature T increases. Thus, we implicitly take the movement of fish in response to local temperature changes into account (cf. 4 Design concepts – Sensing). For each individual, the new location is randomly sampled from a normal distribution with mean value 60km * T/20°C and standard deviation 0.125 * 60km * T/20°C. With increasing temperature, the locations change to higher values and the variation among individual locations increases too (cf. Fig. 3 in the main text).

Fish reproduction. Different locations cause different chances for reproductive success. For each individual, the reproduction rate R depends on location L via R = 1.5 - L/24, and the number of new born individuals is randomly sampled from a Poisson distribution with the rate parameter R. New borns are added to the population up to the current capacity C, which cannot be exceeded. This constraint leads to a dependence of the population reproduction rate on population size, but no functional form of this density dependence is explicitly assumed. (Assigning location and body condition to new individuals is not necessary as they are not affected by further processes and these variables get assigned in the submodels Fish movement and Fish mortality during the next time step.)

Fish mortality. The current river pollution level P and temperature T both affect the body condition B of fish (cf. Fig. 6 in the main text). For each individual, the new value of B is randomly sampled from a normal distribution with mean value (6 - 3 * P/100) * T/20°C and standard deviation 0.1. Thus, body condition decreases with pollution and increases with temperature. The random sampling may yield values for B below 0 or above 1. Such values are replaced by uniform random values between 0 and 0.1 or 0.9 and 1, respectively, to keep B in the allowed range (cf. 2 Entities, state variables and scales). The individuals' mortality rate M depends on B via M = 0.84 - 0.64 * B + *err* (where *err* is a common error for the whole population randomly sampled from a normal distribution with mean value 0 and standard deviation 0.05). Individuals die randomly with a probability equal to their mortality rate M. (If the population happens to exceed the current capacity C at the end of the time step after all processes have been realized, additional randomly selected individuals die until C is reached.)

Fishing. Fishing is adaptive. It takes place only if the population abundance was above a threshold of 150 individuals at the end of the previous time step. In this case, individuals get fished randomly with a probability of 0.2. This means that higher population abundances cause higher annual catch rates (cf. Fig. A2.1).

Literature cited

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