

Supplementary material

Text S1. Submodels of dynamic population model

In the following, the processes occurring in each time step of the dynamic population model are described. Respective parameter values are given in Table 1.

Process 1: Climate state. At the beginning of each time step, the climate state, characterised by temperature and moisture, was updated. Each cell's temperature was calculated by climatological downscaling of mean summer temperature considering altitudinal differences, the adiabatic gradient T_{lapse} and radiation (Moore et al. 1993, Wilson and Gallant 2000, Bellasio et al. 2005):

$$T_{ij} = T - T_{\text{lapse}} \left(\frac{z_{ij}}{1000} \right) + \left(S_{ij} - \frac{1}{S_{ij}} \right) \quad (1)$$

with z_{ij} being the elevation of the grid cell, S_{ij} the ratio between the insolation of the cell and the horizontal surface. The insolation was truncated to the cosine of the solar illumination angle i :

$$\cos(i) = \cos(\theta_0) + \sin(\theta_0) \sin(\text{slope}) \cos(\varphi - A) \quad (2)$$

with the solar zenith angle $\theta_0 = 78.25^\circ$ and the solar azimuth $\varphi = 180^\circ$, A was the aspect and slope the surface slope (Dubayah and Loechel 1997). Potential soil moisture was approximated by the topographic wetness index (Beven and Kirkby 1979, O'Neill et al. 1997), standardised for a precipitation rate of 500 mm/a:

$$W_{ij} = \ln \left(\frac{\text{area}_{ij}}{\tan(\text{slope}_{ij})} \right) \frac{1}{500} \quad (3)$$

where area_{ij} was the drainage area above the cell. Flow directions were assigned using the D8 method, i.e. flow occurred in steepest down-slope direction to one of the cell's eight neighbours, either adjacent or diagonal (Wilson and Gallant 2000). Thus, W_{ij} could be interpreted as the proportion of rainwater each cell was able to retain. Actual soil moisture was then calculated by multiplying the proportion of retained water with actual rainfall.

Process 2: Habitat state. The butterfly depended on the presence and abundance of the plant which induced a carrying capacity K in each lattice cell. K was proportional to the plant foliage projective cover F , with the maximum carrying capacity K_{max} . F was determined by temperature and moisture conditions of a cell, each representing a one-dimensional resource spectrum. The physiological response of the plant was described by a Gaussian utilisation function with the mean being the preferred position in the spectrum and a characteristic variance (May and Mac Arthur 1972). Following Liebig's law of the Minimum which says that growth is controlled by the scarcest resource, the limiting factor, F was calculated by multiplying the degree of utilisation of each resource. Resource competition at plant level was introduced by adding a second plant species, the competitor, whose fundamental niche overlapped with that of the host plant, and which did

not serve as a host plant for the butterfly. The competitor always outcompeted the host plant resulting in a narrower, realised niche of the latter (Fig. 1). To simulate environmental stochasticity, the actual physiological response was drawn from a Normal distribution with mean F and a variance σ_F^2 .

Global dispersal was assumed for host plant and competitor plant. Too abrupt changes in the plant distribution were avoided by incorporating a simple memory effect such that the actual capacity of the new time step was the arithmetic mean between the calculated capacity of time step $t+1$ and the old capacity of time t . This simple memory effect resulted in a time lag of several years.

Process 3: Dispersal. Early in each year, on emergence, a proportion of adult butterflies and parasitoids left their natal patch to colonise other cells in the lattice. Local dispersal was assumed, i.e. the dispersers were concentrated around the area in which they developed as juveniles. The probability p_{ij} that an individual dispersed from cell i to j over the integer distance d_{ij} was described by a two-parameter Weibull distribution allowing different dispersal strategies (Söndgerath & Schröder 2002):

$$p_{ij} = \frac{\exp(-\alpha d_{ij}^\beta)}{\sum_j \exp(-\alpha d_{ij}^\beta)} \quad (4)$$

with the shape parameter β , and the scale parameter α determining the dispersal distance. A high value of α indicated short-range dispersal, a low one large-range dispersal. At $\alpha=0$ the dispersers would be evenly distributed throughout the lattice (global dispersal). The integer distance d_{ij} between cells depended on the applied neighbourhood rule, in this case an 8-cell (Moore) neighbourhood (Hogeweg 1988). Individuals dispersing to unsuitable habitats, i.e. cells without butterfly and plants respectively, died.

Process 4: Reproduction and parasitism. The generalised form of the difference-equation framework for the reproduction and parasitism phase was as follows:

$$\begin{aligned} N_{t+1} &= \lambda N_t g(N_t) f(P_t) \\ P_{t+1} &= c N_t [1 - f(P_t)] \end{aligned} \quad (5)$$

where N and P were the population abundances of the susceptible butterfly stage and the searching adult female parasitoid, respectively, in generations t and $t+1$, λ the net finite rate of increase of the butterfly population, $g(N_t)$ the density-dependent survival of the butterflies progeny, $f(P_t)$ the proportion of butterflies escaping parasitism, c included the average number of adult female parasitoids emerging from each butterfly parasitised. The parasitoids' functional response was linear (type I functional response) and the attacks were randomly distributed amongst the butterfly population (Nicholson 1933, Nicholson and Bailey 1935). The fraction of butterflies escaping parasitism was given by the zero term of a Poisson distribution (eq. 6) with mean aP_t where a was the area of discovery:

$$f(P_t) = \exp(-aP_t) \quad (6)$$

Density dependence of butterfly reproduction entered the model system via $g(N_t)$ (eq. 7), a discrete version of the logistic equation (Ricker 1954, Hassell 2000):

$$g(N_t) = \exp\left(\frac{-\ln(\lambda)}{K} N_t\right) \quad (7)$$

The intrinsic butterfly population growth rate λ was modelled temperature-dependent to reflect its metabolic dependence. To simulate the generally humped-shaped and left-skewed relationship between physiological rates and temperature, a Gumbel distribution was used with T_{opt} as location parameter, a scale parameter σ , and a maximum growth rate λ_{max} . Butterfly population growth rate was additionally restrained by introducing a simple but strong Allee effect (Allee 1931). Below a critical population size N_{crit} , the extinction threshold, no reproduction occurred and the local butterfly population went extinct.

References

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