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# Supplementary material

## Appendix 1

## Detailed model description

### Climate and habitat quality

In order to run a model simulating the effects of climate change, we first have to define how climatic conditions affect the habitat quality in an individual patch in a certain year. To do this we introduce a variable that describes the climatic quality of an individual patch. The climatic quality is a value between zero and one. A climatic quality value of one means the environment is optimal for the species. At zero quality there is no reproduction and mortality is high, resulting in a strongly declining population. We use the average year temperature, i.e. the average of the temperature from 1 January to 31 December, in a patch as predictor of the climatic quality of that patch in that year, because average year temperature is generally considered an important parameter correlating with species range (Bellamy et al. 1998, Jiguet et al. 2006). We derive the average temperature gradient from north to south from data of 9 meteorological stations ranging from Norway to Morocco. A linear regression reveals a temperature gradient of 0.42°C 100 $\text{km}^{-1}$ ($R^2 = 0.94$). Other ecologically important temperature related parameters like the average temperature of the coldest month ($R^2 = 0.95$) and warmest month ($R^2 = 0.89$) are strongly related to the average year temperature. In the model we account for both climate change, that is, the gradual increase in temperature, and for year-to-year variation, since the annual increase in temperature is much less than the year-to-year variation in western European countries (Table 1).

This study considers a climate-driven expansion of a woodland bird along the Atlantic coast of Western Europe. The climate in our model is determined by the average year temperature, a standard deviation of this average temperature of $\sigma_t$ (°C) and a climatic gradient from south to north of $G_t$ (°C $\text{km}^{-1}$). Climate change is defined as an increase of the average year temperature of $I_t$ (°C $\text{yr}^{-1}$). From these data we calculate, respectively, the speed of travel of isotemperature lines ($V_c$ km $\text{yr}^{-1}$) from south to north, and the fluctuation ($\sigma_d$ km) of these lines:

$$V_c = I_t / G_t \text{ and } \sigma_d = \sigma_t / G_t \tag{A1a, b}$$

$\sigma_t = 0.59$ (°C) was derived from the variation in Dutch (station: de Bilt) meteorological data of last century relative to a moving average of 10 yr.

Suppose there is an optimal isotemperature line where the habitat quality is one. This optimal temperature isocline moves northward with speed $V_c$ but has a yearly fluctuation of $\sigma_d$. So the position in the north-south direction of the optimal isocline ($Y_{opt}$) after t years is

$$Y_{opt,t} = Y_{opt,0} + V_c \cdot t + \sigma_d \cdot N_t \tag{A2}$$

where $N_t$ is drawn for a standardised normal distribution.

To determine the climatic quality of individual patches, we assume a bell-shaped curve with the optimal isotemperature line in the centre (Bowers and Harris 1994). Given a certain position of the optimal isotemperature line at a certain time ($Y_{opt,t}$ ) and patch location ($Y_{patch}$) the quality of a patch is

$$Q_{patch,t} = \exp\left[\frac{-0.695(Y_{opt,t} - Y_{patch})^2}{H^2}\right] \tag{A3}$$

Here, H represents the temperature tolerance of the species, indicating the deviation with respect to the location of optimum temperature at which the habitat quality is 0.5 (this makes the value 0.695 necessary). The result is a bell-shaped curve reflecting the habitat quality that is gradually moving northwards but has large fluctuations due to climatic variation (Fig. 2).

### Reproduction

At the start of a year only adults are present in a habitat patch (Fig. 1). The minimum number of females and males and the carrying capacity together determines the number of reproductive units in a specific patch. The recruitment, the expected number of juveniles per reproductive unit surviving the first year, is drawn from a Poisson distribution with the parameter $R_{q,d}$ representing the expected number of offspring surviving and its variance. The parameter $R_{q,d}$ is linearly dependent on both climatic quality Q and the relative density D in the following way:

$$R_{q,d} = \left(1 - (1 - R_{0,0} / R_{1,0}) \cdot (1 - Q)\right) \cdot \left(1 - (1 - R_{1,1} / R_{1,0}) \cdot D\right) \cdot R_{1,0} \tag{A4}$$

Here $R_{Q,D}$ are reference values for the reproduction at quality Q and the relative density D. The relative density D is calculated in the following way:

$$D = \frac{RU \cdot A_r}{A_P} \tag{A5}$$

Here RU is the number of reproductive units in the patch being the minimum of adult males and females, $A_r$ is the area requirement of a reproductive unit (Table 1) and $A_P$ is the patch area.

## Dispersal

The probability to disperse $P_{q,d}$ for both juveniles and adults is also density and quality dependent. At low densities and high quality the probability to disperse is low while at high densities and low quality the probability to disperse is high. Analogous to recruitment, the density and quality dependency of dispersal is calculated with the help of reference values:

$$P_{q,d} = \left(1-(1-P_{0,0}/P_{0,1})\cdot(1-D)\right)\cdot\left(1-(1-P_{1,1}/P_{0,1})\cdot Q\right)\cdot P_{0,1} \tag{A6}$$

and values of $P_{q,d}$ are truncated to one for a values higher than one. We assume that patches are circular. We use a connectivity routine in which the diameter and the distance of a target patch determine the connectivity from the reference patch to the neighbouring patch (Nicholson et al. 2006). Thus, the probability ($P_{1\to 2}$) that a disperser goes from patch 1 to patch 2 is:

$$P_{1\to 2} = \frac{2\cdot \arcsin(\frac{z+r_2}{d})}{2\cdot \pi} \tag{A7}$$

Here $r_2$ is the radius of patch 2, d is the distance between patch 1 and patch 2, and z is the detection radius of the bird, the distance from the patch within which the bird is attracted to the destination patch. This routine, however, considers only patches within a critical maximum radius M from the patch of origin. The model does not allow dispersers to ignore a nearer patch, so more distant patches are located in the shadow of a nearer patch. Hence, the sum of all the probabilities cannot exceed one. Upon arrival in a new patch, an individual may stay or may leave for another patch, again according to equation 6. We do not expect individuals to disperse forever. Therefore the animals are allowed to have three dispersal rounds per year, so they may theoretically move three times their maximum dispersal distance M from the source patch. Individuals that do not find another patch within these three rounds die.

## Adult survival and maturation

Adult survival is quality dependent and determined by two parameters: survival at a quality of one ($S_1$) and survival at a quality of zero ($S_0$). Between these values the survival is linearly interpolated. At the end of the year juveniles become adults and are able to reproduce (Fig. 1).

## Parameterization of the model

We parameterize our woodland bird species using the traits of the middle spotted woodpecker *Dendrocopus medius*. Parameters from the literature cannot be applied without adjustment, because the model requires parameters for different habitat quality and density values. The field data usually come from studies with unknown habitat quality and population density. Therefore, we calibrated survival parameters to meet population survival probabilities for medium-sized vertebrates as defined by Verboom et al. (2001). To compensate for climatic fluctuations and quality, we have to increase the value for adult survival from the value 0.7, as found in the literature (Kosenko and Kaigorodova 2001, Michalek and Winkler 2001, Kosinski and Ksit 2006), to 0.8 for a habitat quality of one (optimal habitat).

There is a lack of species specific data about the dispersal probability in the middle spotted woodpecker. So we use dispersal probability values used by Vos et al. (2001). Furthermore we expect that species tend to disperse less at low densities (Travis et al. 1999).