Supplementary material: Mixed use landscapes can promote range expansion (Crone et al.)

S1. List of studies with movement in high- and low-quality environments

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S2. Taxonomic distribution of studies with movement in high- and low-quality environments

Taxonomic distribution of studies included in our analysis of empirical patterns

Phylum	Class	Order	# studies
Arthropoda	Arachnida	Trombidiformes	2
Arthropoda	Entognatha	Collembola	2
Arthropoda	Insecta	Blattodea	2
Arthropoda	Insecta	Coleoptera	9
Arthropoda	Insecta	Hemiptera	4
Arthropoda	Insecta	Hymenoptera	3
Arthropoda	Insecta	Lepidoptera	23
Arthropoda	Insecta	Odonata	2
Arthropoda	Insecta	Orthoptera	4
Arthropoda	Maxillopoda	Calanoida	1
Chordata	Aves	Anseriformes	1
Chordata	Aves	Apodiformes	2
Chordata	Aves	Charadriiformes	4
Chordata	Aves	Suliformes	2
Chordata	Mammalia	Artiodactyla	4
Chordata	Mammalia	Carnivora	1
Chordata	Mammalia	Diprotodontia	1
Chordata	Mammalia	Rodentia	1
Chordata	Reptilia	Testudines	2
Ciliophora	Ciliatea	Hymenostomatida	1
Cnidaria	Scyphozoa	Semaeostomeae	1
Echinodermata	Echinoida	Strongylocentrotidae	1
Mollusca	Gastropoda	Neotaenioglossa	2
Myxomycota	Myxomycetes	Physarales	1
Rotifera	Monogonta	Ploima	2

S3. AIC model comparison of GLMMs of movement in high- and low-quality habitats with random effects of taxonomy.

"Variance" refers to the magnitude of the estimated variance associated wth that level. The model with the lowest AIC is the best model for a given data set. In this case the winning model has no taxonomic random effects. "All" refers to a model with Phylum, Class, Order and Family included simultaneously. Models with Genus and Species as random effects showed signs of overparameterization, presumably due to low replication at these levels.

Random effect	df	Variance	AIC
Phylum	2	0.00	64.2
Class	2	0.00	64.2
Order	2	0.34	64.0
Family	2	0.35	64.2
none	1	NA	62.2
All	5	--	70.0

S4. Dispersion Relation

Here, we demonstrate that the dispersion relation in Musgrave and Lutscher (2014) also applies under slightly different mechanistic assumptions about the oviposition process than were presented in their original manuscript. Musgrave and Lutscher (2014) considered a dispersal process whereby each female starts with a certain number of eggs, and these eggs are deposited at a constant rate per unit time per egg. Alternatively, one can consider a process whereby each female can produce and deposit eggs at a constant rate per unit time. Here, we present a model for the latter scenario and show that its dispersion relation is of the exact same form as that derived by Musgrave and Lutscher (2014), albeit with appropriately adjusted parameters.

We begin by modeling the dispersal process. We denote by $u(t,x)$ the probability density function of a female butterfly during the dispersal process. We consider ecological diffusion (Turchin 1998) with motility $D(x)$ and mortality $m(x)$. The equation for density is

$$\frac{\partial}{\partial t}u(t,x) = \frac{\partial^2}{\partial x^2}\big(D(x)u(t,x)\big) - m(x)u(t,x).$$

The initial condition $u(0,x) = \delta(x-y)$ indicates y as the location where the female started its ovipositioning process. Here, $\delta(x)$ stands for the Dirac delta distribution. We assume that $D(x)$ and $m(x)$ are periodic functions of period L.

Next, we denote by $a(x)$ the rate of egg deposition (per unit time per female). Then the density (but not probability density) of eggs deposited by a single female who started the dispersal process at location y is given by

$$K(x,y) = \int_0^\infty a(x)u(t,x)dt.$$

Now we include this process into the population dynamics model form one generation to the next. We denote by $N_t(x)$ the density of deposited eggs at the end of one year, and by $p(x)$ the probability that an egg at location x will develop into a gravid female in the following year. Then the density of eggs in the next year can be obtained by summing all the eggs that were deposited by females who emerged from eggs in the previous year. In formulas, this reads

$$N_{t+1}(x) = \int_{-\infty}^{\infty} K(x,y)p(y)N_t(y)dy.$$

We want to calculate the speed with which the population spreads across the landscape. We make the usual ansatz for a traveling periodic wave (Kawasaki and Shigesada 2007) as

$$N_t(x) = e^{-s(x-ct)}T(x),$$

where $T(x)$ is also a function of period L. In this ansatz, c is the speed of the wave and s its shape parameter that indicates how quickly the traveling periodic wave drops off to zero at the leading edge. Substituting this ansatz into the equation for $N_t(x)$ above, we obtain the relation

$$e^{sc}e^{-sx}T(x) = \int_{-\infty}^{\infty} K(x,y)p(y)e^{-sy}T(y)dy.$$

This is an eigenvalue problem with an integral operator, the eigenvalue being e^{sc}. For a general kernel function, it can be solved numerically. However, for the kernel defined by the ovipositioning model above, we can turn the integral equation into a differential equation as follows.

We integrate the equation for $u(t,x)$ with respect to time from 0 to infinity, i.e.

$$\int_0^\infty \frac{\partial}{\partial t} u(t,x)dt = \int_0^\infty \frac{\partial^2}{\partial x^2}[D(x)u(t,x)] - m(x)u(t,x)dt.$$

On the left hand side of this equation, we find

$$\int_0^\infty u_t(t,x)dt = u(\infty,x) - u(0,x) = -\delta(x-y)$$

since $u(\infty,x) = 0$ for all x.

On the right hand side, we multiply and divide by $a(x)$ and move the terms that are independent of time out of the integral. We obtain

$$\frac{\partial^2}{\partial x^2}\left[\frac{D(x)}{a(x)}\int_0^\infty a(x)u(t,x)dt\right] - \frac{m(x)}{a(x)}\int_0^\infty a(x)u(t,x)dt = \frac{\partial^2}{\partial x^2}\left[\frac{D(x)}{a(x)}K(x,y)\right] - \frac{m(x)}{a(x)}K(x,y).$$

We denote the linear differential operator on the right hand side of this expression by L, i.e.

$$LK(x,y) = \frac{\partial^2}{\partial x^2}\left[\frac{D(x)}{a(x)}K(x,y)\right] - \frac{m(x)}{a(x)}K(x,y).$$

Putting together the left and right side of the above equation, we find

$$LK(x,y) = -\delta(x-y).$$

We apply the operator L to both sides of the integral eigenvalue problem. We find

$$e^{sc}L[e^{-sx}T(x)] = -\int_{-\infty}^{\infty} \delta(x-y)p(y)e^{-sy}T(y)dy = -p(x)e^{-sx}T(x).$$

This is now a differential equation eigenvalue problem. After some rearrangement, we find

$$\frac{\partial^2}{\partial x^2}\left[\frac{D(x)}{a(x)}e^{-sx}T(x)\right] - \frac{m(x)}{a(x)}e^{-sx}T(x)\left[e^{-sc}p(x)\frac{m(x)}{a(x)} - 1\right] = 0.$$

As the final step, we denote

$$\psi(x) = \frac{D(x)}{a(x)}e^{-sx}T(x), \qquad \hat{r}(x) = p(x)\frac{a(x)}{m(x)}, \qquad \mu(x) = \sqrt{\frac{m(x)}{D(x)}}.$$

Then the differential equation turns into

$$\psi''(x) - \mu(x)^2\psi(x)[\,e^{-sc}\hat{r}(x) - 1] = 0.$$

This is exactly formula 80 in Musgrave and Lutscher (2014) from which they derive the dispersion relation.

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S5. Data used to evaluate movement / habitat-quality tradeoffs

Phylum	Class	Order	Family	Genus	Species	Conclusion	Ranks
Chordata	Mammalia	Artiodactyla	Cervidae	Rangifer	Rangifer tarandus caribou	YES	0
Arthropoda	Insecta	Hymenoptera	Mymaridae	Anagrus	Anargus nigriventris	YES	0
Chordata	Aves	Charadriiformes	Alcidae	Uria	Uria aalge	YES	0
Chordata	Aves	Charadriiformes	Scolopacidae	Limosa	Limosa limosa	YES	0
Chordata	Aves	Charadriiformes	Scolopacidae	Tringa	Tringa totanus	NO	2
Chordata	Aves	Charadriiformes	Recurvirostridae	Recurvirostra	Recurvirostra avosetta	NO	2
Arthropoda	Insecta	Lepidoptera	Geometridae	Speranza	Speranza andersoni	YES	0
Chordata	Reptilia	Testudines	Dermochelyidae	Dermochelys	Dermochelys coriacea	YES	0
Chordata	Mammalia	Artiodactyla	Cervidae	Cervus	Cervus elaphus canadensis	NO PATTERN	1
Ciliophora	Ciliatea	Hymenostomatida	Tetrahymenidae	Tetrahymena	Tetrahymena pyriformis	NO PATTERN	1
Arthropoda	Insecta	Coleoptera	Coccinellidae	Coccinella	Coccinella septempunctata	YES	0
Chordata	Aves	Anseriformes	Anatidae	Cygnus	Cygnus columbianus bewickii	YES	0
Mollusca	Gastropoda	Neotaenioglossa	Hydrobiidae	Hydrobia	Hydrobia ulvae	NO PATTERN	1
Rotifera	Monogonta	Ploima	Brachionidae	Brachionus	Brachionus calyciflorus	YES	0
Rotifera	Monogonta	Ploima	Brachionidae	Brachionus	Brachionus calyciflorus	YES	0
Chordata	Aves	Suliformes	Sulidae	Morus	Morus capensis	YES	0
Chordata	Aves	Suliformes	Sulidae	Morus	Morus bassanus	YES	0

Arthropoda	Entognatha	Collembola	Onychiuridae	Protaphorura	Protaphorura armata	YES	0
Myxomycota	Myxomycetes	Physarales	Didymiaceae	Didymium	Didymium spp	NO PATTERN	1
Mollusca	Gastropoda	Neotaenioglossa	Thiaridae	Tarebia	Tarebia granifera	NO	2
Arthropoda	Insecta	Coleoptera	Carabidae	Pterostichus	Pterostichus melanarius	NO	2
Arthropoda	Insecta	Hemiptera	Delphacidae	Prokelisia	Prokelisia crocea	YES	0
Arthropoda	Insecta	Coleoptera	Tenebrionidae	Eleodes	spp	YES	0
Arthropoda	Insecta	Orthoptera	Tettigoniidae	Bicolorana	Bicolorana bicolor	YES	0
Arthropoda	Insecta	Lepidoptera	Nymphalidae	Melitaea	Melitaea diamina	NO	2
Arthropoda	Insecta	Lepidoptera	Erebidae	Lymantria	Lymantria dispar	YES	0
Arthropoda	Arachnida	Trombidiformes	Tetranychidae	Tetranychus	Tetranychus urticae	YES	0
Arthropoda	Insecta	Lepidoptera	Geometridae	Asthena	Asthena albulata	YES	0
Arthropoda	Insecta	Lepidoptera	Pieridae	Pieris	Pieris rapae	NO PATTERN	1
Arthropoda	Insecta	Coleoptera	Chrysomelidae	Phyllotreta	Phyllotreta cruciferae	NO	2
Arthropoda	Insecta	Coleoptera	Chrysomelidae	Phyllotreta	Phyllotreta striolata	NO	2
Arthropoda	Insecta	Lepidoptera	Nymphalidae	Euphydryas	Euphydryas anicia	YES	0
Arthropoda	Insecta	Hemiptera	Cicadellidae	Dalbulus	Dalbulus maidis	YES	0
Arthropoda	Insecta	Hemiptera	Aphididae	Acyrthosiphon	Acyrthosiphon pisum	YES	0
Arthropoda	Insecta	Lepidoptera	Pieridae	Pieris	Pieris rapae	YES	0
Arthropoda	Insecta	Lepidoptera	Pieridae	Colias	Colias philodice	YES	0
Arthropoda	Insecta	Lepidoptera	Gelechiidae	Phthorimaea	Phthorimaea operculella	NO	2
Arthropoda	Insecta	Lepidoptera	Pieridae	Aporia	Aporia crataegi	YES	0

Arthropoda	Insecta	Lepidoptera	Nymphalidae	Danaus	Danaus plexippus	YES	0
Arthropoda	Insecta	Lepidoptera	Nymphalidae	Euphydryas	Euphydryas anicia	YES	0
Echinodermata	Echinoida	Strongylocentrotidae		Strongylocentrotus	Strongylocentrotus droebachiensis	YES	0
Arthropoda	Insecta	Blattodea	Rhinotermitidae	Reticulitermes	Reticulitermes flavipes	YES	0
Arthropoda	Insecta	Blattodea	Rhinotermitidae	Coptotermes	Coptotermes formosanus	NO PATTERN	1
Chordata	Mammalia	Rodentia	Cricetidae	Peromyscus	Peromyscus maniculatus	YES	0
Arthropoda	Arachnida	Trombidiformes	Tetranychidae	Tetranychus	Tetranychus urticae	YES	0
Arthropoda	Insecta	Lepidoptera	Nymphalidae	Coenonympha	Coenonympha tullia nipisiquit	YES	0
Chordata	Mammalia	Artiodactyla	Bovidae	Gazella	Gazella dorcas	YES	0
Arthropoda	Insecta	Coleoptera	Chrysomelidae	Trirhabda	Trirhabda borealis	YES	0
Chordata	Aves	Apodiformes	Trochilidae	Selasphorus	Selasphorus platycercus	YES	0
Chordata	Aves	Apodiformes	Trochilidae	Selasphorus	Selasphorus rufus	YES	0
Arthropoda	Insecta	Odonata	Calopterygidae	Calopteryx	Calopteryx aequabilis	YES	0
Arthropoda	Insecta	Odonata	Calopterygidae	Calopteryx	Calopteryx maculata	YES	0
Arthropoda	Insecta	Hymenoptera	Mymaridae	Anagrus	Anagrus columbi	NO PATTERN	1
Arthropoda	Insecta	Coleoptera	Coccinellidae	Coleomegilla	Coleomegilla maculata	YES	0
Arthropoda	Insecta	Orthoptera	Acrididae	Opeia	Opeia obscura	NO	2
Arthropoda	Insecta	Hemiptera	Delphacidae	Prokelisia	Prokelisia crocea	NO PATTERN	1

Arthropoda	Insecta	Coleoptera	Passalidae	Odontotaenius	Odontotaenius disjunctus	NO	2
Cnidaria	Scyphozoa	Semaeostomeae	Pelagiidae	Chrysaora	Chrysaora quinquecirrha	YES	0
Arthropoda	Insecta	Lepidoptera	Papilionidae	Parnassius	Parnassius smintheus	NO PATTERN	1
Arthropoda	Insecta	Hymenoptera	Apidae	Bombus	Bombus occidentalis	YES	0
Arthropoda	Insecta	Orthoptera	Gryllidae	Nemobius	Nemobius sylvestris	YES	0
Arthropoda	Insecta	Coleoptera	Chrysomelidae	Chrysolina	Chrysolina graminis	YES	0
Arthropoda	Insecta	Orthoptera	Tettigoniidae	Platycleis	Platycleis albopunctata	YES	0
Arthropoda	Insecta	Lepidoptera	Pieridae	Abaeis	Abaeis nicippe	YES	0
Arthropoda	Insecta	Lepidoptera	Pieridae	Phoebis	Phoebis sennae	YES	0
Arthropoda	Insecta	Lepidoptera	Papilionidae	Papilio	Papilio troilus	YES	0
Chordata	Mammalia	Artiodactyla	Bovidae	Capra	Capra hircus	YES	0
Chordata	Mammalia	Carnivora	Felidae	Panthera	Panthera leo	YES	0
Chordata	Reptilia	Testudines	Emydidae	Terrapene	Terrapene ornata	NO PATTERN	1
Arthropoda	Insecta	Lepidoptera	Papilionidae	Parnassius	Parnassius smintheus	NO	2
Chordata	Mammalia	Diprotodontia	Potoroidae	Bettongia	Bettongia tropica	YES	0
Arthropoda	Maxillopoda	Calanoida	Acartiidae	Acartia	Acartia clausi	YES	0
Arthropoda	Entognatha	Collembola	Onychiuridae	Protaphorura	Protaphorura armata	YES	0
Arthropoda	Insecta	Lepidoptera	Lycaenidae	Plebejus	Plebejus icarioides fenderii	YES	0
Arthropoda	Insecta	Lepidoptera	Nymphalidae	Euphydryas	Euphydryas phaeton	YES	0
Arthropoda	Insecta	Lepidoptera	Nymphalidae	Lethe	Lethe appalachia	YES	0

Arthropoda	Insecta	Lepidoptera	Nymphalidae	Maniola	Maniola jurtina	YES	0
Arthropoda	Insecta	Lepidoptera	Lycaenidae	Plebejus	Plebejus icarioides fenderii	YES	0