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Appendix 1.

Algorithmic description of the agent-based model

In this supplementary material section we will give a precise definition of the agent based model such that it can be easily implemented. The motivation and the outline are described in the Model assumptions and parameters section of the main paper.

The landscape, in the agent-based model, will be represented by a square grid of L-by-L pixels. There are, in general, two types of pixels – those that never contain food (non-patch pixels) and those that can contain food (patch pixels). A patch is a connected set of patch pixels, i.e. one can go from one pixel in the patch to any other by moving in the four cardinal directions without stepping on a non-patch pixel. If the forager steps on a food containing pixel it turns empty and stays empty for $t_{regrowth}$ time steps.

At a given time the forager can be in two modes: traveling (when it is traveling to a new patch filled with food) or searching (when the agent is foraging food within a patch). The searching mode lasts t_{stay} time steps, whereas the traveling mode lasts until the forager steps on a pixel of a patch fully loaded with food. The accumulated energy at a time t is given by E(t). In the traveling mode the forager loses E_{stay} t_T units of energy every time step. In foraging mode it loses one unit of energy every time step and gains E_F units if food is encountered.

In traveling mode the forager follows a biased random walk. Let d(x,y) be the Euclidean distance between the (x,y)-pixel and the closest pixel in a patch fully loaded with food. Then the probability to step on a pixel (x,y) is proportional to

$$P(x,y) = \exp(-d(x,y) / \delta) \ , \qquad \text{(S1-1)}$$

where δ is a parameter controlling the accuracy of the walk. To implement this, one has to make contiguous intervals of length P(x + 1, y), P(x – 1, y), P(x, y + 1) and P(x, y – 1) (and omit any pixel that is outside the grid boundary), then generate a random number between zero and the sum of the intervals. Then, the corresponding pixel whose interval the number falls in will be selected. If, for example a pixel at distance 3 from a patch is surrounded by two pixels $\mathbf{p}_1$ and $\mathbf{p}_2$ at distance 2 from a patch, and two pixels $\mathbf{p}_1$ and $\mathbf{p}_2$ at distance 4 from a patch; then the probability for the forager to move to $\mathbf{p}_3$ and $\mathbf{p}_4$ is

$$P_{12} = \exp(-2/\delta) \ / \ [2 \exp(-2/\delta) + 2 \exp(-4/\delta)] \qquad \text{(S1-2)}$$

whereas the probability to move to $\mathbf{p}_3$ or $\mathbf{p}_4$ is

$$P_{34} = \exp(-4/\delta) \ / \ [2 \exp(-2/\delta) + 2 \exp(-4/\delta)] \ . \qquad \text{(S1-3)}$$

In this example it is thus

$$P_{12} \ / \ P_{34} = \exp(2/\delta) \qquad \text{(S1-4)}$$

times more likely that the forager moves closer to a patch, than that it moves further away from a patch. If δ is larger, then the probability of moving closer to a patch decrease, so δ functions as a control parameter for the randomness of the navigation. Eq. S1-4 can easily be generalized to reach the same conclusion about the function of δ.

In foraging mode the motion of the agent is an unbiased random walk. The pixel to go to is selected with uniform randomness among the pixels within a patch (regardless of the status of the patch, food-containing or empty).

All patch pixels are initialized as food-containing and the forager is placed on a random pixel in an L-by-L square grid. Before $t_{regrowth}$ time steps elapses after the first food-containing pixel is encountered, the landscape will have more food than on average. During this transient, quantities should thus not be measured.

1. If the agent, currently at pixel (x,y), is in foraging mode:
   a. If there is food at (x,y): Let E(t + 1) = E(t) + E_F – 1. Mark the pixel as empty.
   b. If there is no food at (x,y): Let E(t + 1) = E(t) – 1.
   c. Go to a random Moore neighbor within the patch, i.e. one of (x + 1, y), (x – 1, y), (x, y + 1) and (x, y – 1).
   d. If the forager has been within the patch for t_{stay} time steps, change to traveling mode.
2. If the agent is in traveling mode:
   a. Let E(t + 1) = E(t) – E_T.
   b. Move to a Moore neighbor with probability given by eq. (S1-1).
   c. If the new pixel belongs to a patch where all pixels are food-containing, change to foraging mode.
3. Check all the pixels of all patches. If any of these has been empty for t_{stay} time steps, let it contain food.

Appendix 2.

Model for generating landscapes with tunable clumpiness, a detailed description

In this supplementary material section, we present the model for generating patches with tunable clumpiness in greater detail. The algorithm starts with an empty square grid representing a landscape. It proceeds by iteratively adding circular patches of radius r such that no two patches are in contact. The adding is stopped when a total fraction f of the landscape is filled with patches. To be able to control the clumpiness we restrict the patches to the interior of N circles of radii $R = \rho / L$. These larger circles are also placed out randomly but without the requirement that they should not overlap. A small ρ (and thus a small R) gives more tightly packed patches (i.e. greater clumpiness). ρ is our control parameter for clumpiness but since the average clumpiness decrease with ρ we term it the unclumpiness parameter. To summarize the algorithm proceeds as follows:

1. Scatter, with uniform randomness, N circles of radii R over the landscape. The only requirement is that their centers are within the landscape. They may overlap.
2. Fill, iteratively with uniform randomness, the area within the circles with patches of radius r in such a way that no two patches are in contact and a fraction f of the original landscape is covered by patches.

(See Fig. 1.)

In the language of geometrical statistics, the centers (or grains) of the superpatches form a homogeneous binomial field (Diggle 1983). Let Ω be the set of points closer than R to a grain, then patches is a simple sequential inhibition field of discs of radius r (Stoyan and Stoyan 1994). A common quantity to characterize clustered models is the pair-correlation function g(l) – the probability density for another point to exist at distance l from a point, normalized by the average point density (so that g(l) = 1 for an uncorrelated random distribution). In a landscape of high clumpiness, g(l) should reveal the size of a patch as well as the size of a superpatch. In Fig. S1 we plot g(l) for r = 0.15 and $\rho = \infty$ (other parameter values are like in the rest of the paper). For the clumpier landscape ($\rho = 0.15$) the diameter of both the patches, and superpatches, are visible as g flattens out when l increases beyond the diameter of a patch, and superpatch, respectively.

The parameter R cannot be arbitrarily small – there has to be enough space to place the patches. In an intermediate region there can sometimes (i.e., for some random seeds) be enough space to place all patches, sometimes not. In these cases we discard the cases where the algorithm gets stuck. Another aspect is that the total area within the large patches demarcated by the radius-R circles is not linearly dependent on ρ – if R is large a small increase of R will not affect the area where patches can be placed much. In the region of parameter space we use, however, the fraction of the area is steadily increasing (Fig. S2).

References

Diggle, P. J. 1983. Stochastical analysis of point processes. – Academic Press.

Stoyan, D. and Stoyan, H. 1994. Fractals, random shapes and point fields: methods of geometrical statistics. – Whiley.

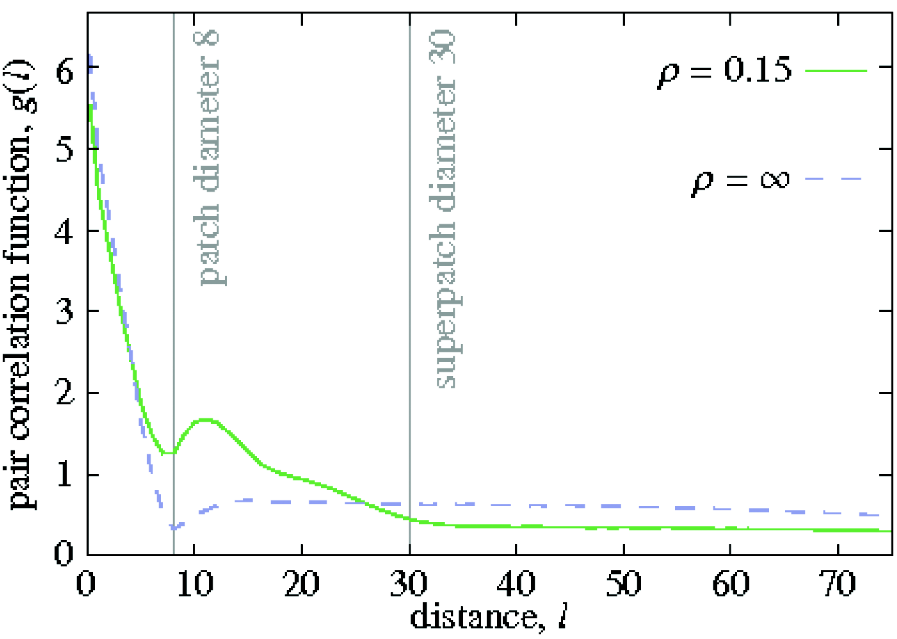

Fig. S1. The pair-correlation function for our model of landscapes with tunable clumpiness. The solid green line marks the clumpy landscape (with r = 0.15), the dashed grey line is the random landscape. Other parameters are like Fig. 2.

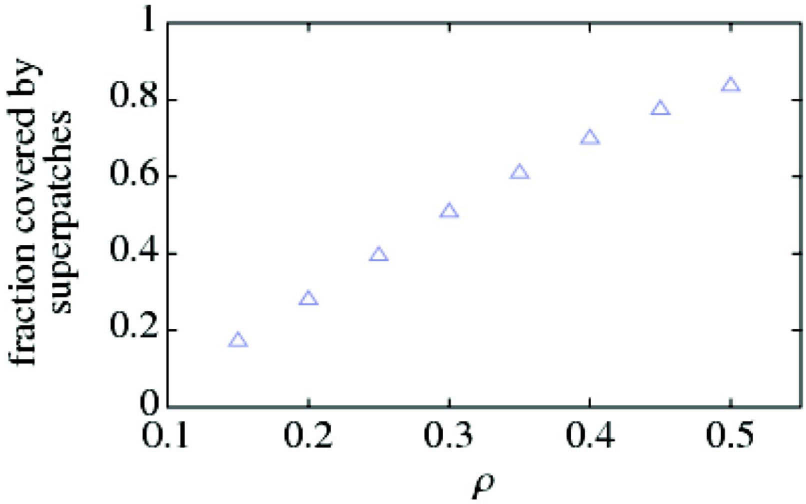

Fig. S2. The area of superpatches (for potential placement of patches; enclosed by circles of radius R) as a function of unclumpiness r. The other parameter values are L = 100, N = 3, as in Fig. 2.