Expansion, Exploitation and Extinction: Niche Construction in Ephemeral Landscapes

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Abstract
We developed an interacting particle system (IPS) to study the effect of niche construction on metapopulation dynamics in ephemeral landscapes. Using finite scaling theory, we find a divergence in the qualitative behavior at the extinction threshold between analytic (mean field) and numerical (IPS) results when niche construction is confined to a small area in the spatial model. While increasing the area of niche construction leads to a faster rate of range expansion, it also causes a shift from a continuous to discontinuous phase transition, thus returning to the mean field prediction. Furthermore, in the discontinuous regime of the IPS, spatial clustering prior to a critical transition disappears. This is a significant finding as spatial clustering has been considered to be an early warning signal before ecosystems reach their ‘tipping point’. In addition to maintaining stability, we find this local niche construction strategy has an advantage when in competition with an exploiter because of their ability to monopolize the constructed niche due to spatial adjacency. However, as the niche construction neighborhood expands this advantage disappears and the exploiter strategy out-competes the niche constructor. In some cases the exploiter pushes the niche constructor to extinction, thus a tragedy of the commons ensues leading to ecological suicide and a collapse of the niche.

Full-text
Due to technical limitations, full-text HTML conversion of this manuscript could not be completed. However, the manuscript can be downloaded and accessed as a PDF from the Manuscript Files section below.

Figures
NC Reactions and the Colonization-Construction Trade-off. Left: Schematic showing the reactions for the NC model. The probability of colonization ($1\cdot c$) and construction $c$ events occurring are dependent on the density ($\rho$) of occupied sites within the colonization and construction range ($r$) of the stochastic process ($\xi$). Sites in the lattice acquire one of 3 possible states, $S = \{1, ?, 1\}$, so the state of the system at time $t$ is $t : L \oplus S$. Right: Trade-off between construction ($x$-axis) and colonization ($y$-axis) with respect to 3 different values of $\alpha$. 
Figure 2

Long-term behavior of the NC Model. Top: A comparison of the MFA (Left) and the IPS (Right) parameter spaces, with the x-axis signifying the life-history strategy adopted (c) and the y-axis the hostility of the landscape (e). For both $\phi = 0:1$ and $\phi = 1$. For IPS, simulations ran for 5000 times steps, where, upon reaching the invariant measure, a mean occupancy $\hat{p}_+i$ was calculated from the following 250 time steps. In total, 10,000 simulations were run by sweeping the parameter space $fc$; eg creating a 100x100 matrix. Bottom: Divergence in the qualitative behavior of the niche construction model. For the MFA a discontinuous transition exists for the order parameter $bp+$, whereas the discontinuity disappears in the IPS for $r = 1$ and we are left with a continuous transition, similar to the CP. Other parameters for MFA and IPS $f$; $cg = f1; 0; 0:4g$.
Left: Snapshots of the particle system at $t = 1000; 2500; 5000$. Occupied (green), Vacant (white) & Destroyed (black) sites. Right: A 1D spatial transect of the particle system for 256 time steps. After a transient period ($t$) the nal snapshot/transect shows the system after it has reached the invariant measure ($\phi$). Parameter values used for this simulation were at the edge near the extinction threshold (See IPS in Figure 2); $f; c_1 = 1; 0.1; 0.25; 0.045g$.
Figure 4

Left: Log-log plot showing critical behavior of the order parameter (long-term occupancy, $\langle p_+ \rangle$) as we approach the critical point $c_\text{rit}$ and $e_\text{crit}$ for the contact process (black) and NC model (green), respectively. As these systems near the critical point ($k < k_{\text{crit}}$ for $k = e$), the order parameters display power law behavior with unique critical exponents (indicated by the unique slope for each). The critical exponent for the contact process determined from this slope ($0.6116$) holds up well against previous estimates ($50$).

Parameters for the niche construction model $f; ; cg = f_1; 0; 0.4g$. Right: Dynamical behavior for the Niche Construction model (Top) and Contact process (Bottom) for $k < k_{\text{crit}}$ (subcritical), $k = k_{\text{crit}}$ (critical) and $k > k_{\text{crit}}$ (supercritical), from top to bottom in each plot.

Divergence of relaxation time to extinction at the critical point is indicative of continuous phase transitions.
Figure 5

Range expansion for niche constructor strategies with different r. After a transient period of expansion (t) which decreased as r increased, identical hp+i were reached for ecrit. The solid and consequent dotted vertical lines indicate the times (t) when each strategy (r = 10; 9; ::; 1) reached hp+i. Simulations were run with the following parameter values f; c; eg = f1; 0:1; 0:4; 0:01g. Bottom: Longterm behavior for different r around ecrit (Left). Parameters used for simulations were f; cg = f1; 0; 0:4g. Snapshots showing differences in spatial clustering taken from simulations at e = 0:088 for r = 10 and r = 1.
Figure 6

Top Left: Updated schematic of model with NC (green) and ES (red) competing for space.

Bottom Left: Trajectories of the NC-ES phase space for different r values. Larger values of r increase the likelihood of ecological suicide during the transient period. Oscillations are caused by range expansion/exploitation of the NC/ES populations. If the NC metapopulation can escape the rst wave of exploitation from the ES strategy then coexistence is likely.

Center: Population dynamics for global (top) and r = 1 (bottom) niche construction neighborhood following niche constructor (green) contact process (red) strategies along with destroyed habitat (black) in the coexistence regime: f; ; c; eg = f1; 0:1; 0:4; 0:01g.

Right: Four snapshots taken at t = 250; 1000; 2000; 4000 from top to bottom, temporal locations of snapshots are indicated with vertical dashed lines. Frame 1 shows the ES population being fragmented from vacant sites due to habitat destruction, but rescued by the NC population expanding via the construction of viable habitat. Once the ES population establishes itself within the connes of the surrounding NC particles (frame 2 and 3) they can begin exploiting this renewed habitat and freshly vacated sites (generated by c and , respectively) due to their superior colonization rate ( > ~). Notice the trail of destroyed
habitat as this ES metapopulation follows the leading wave of the NC metapopulation outward, occasionally becoming fragmented from empty sites and therefore destined for local extinction. Eventually, the system equilibrates, although small fluctuations continue due to the local oscillations and the finite size of the landscape, see (56) for a discussion on this with respect to lattice models.

Parameter space fc\(; eg\) for the model with competition. Left, center and right columns correspond to mean occupancy for NC, ES and both strategies \((p = p_+ + p++)\), respectively. Three niche construction neighborhoods \(r = 1; 4; 7\) from top to bottom. f; g = f1; 0:1g. As \(r\) increases ecological extinction expands where ES overexploits NC. The noisiness of this transition, exemplified by spotted pattern of the parameter space, is explained in the main text.
Figure 8

Comparing the niche construction efficacy on long term values $hp+i$ for the single strategy model as $e$ increases.