Emergence of Cooperative and Competitive Resource Networks through Evolution of Niche Construction and Ecological Inheritance

Nomado Umino, Takaya Arita and Reiji Suzuki

Graduate School of Information Science, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
umino.nomado.a3@s.mail.nagoya-u.ac.jp

Abstract

Niche construction, in which organisms modify selective pressures, can lead to unexpected evolutionary outcomes. This study investigates how substantial environmental modifications that redistribute resources—exemplified by human culture and social insect architecture—emerge through the evolution of reproduction and niche-constructing behaviors. We present an evolutionary model of resource-redistributive niche construction on a two-dimensional grid, where "pipes" transport resources between adjacent cells. These pipes persist across generations but decay through weathering, enabling ecological inheritance, and can connect to form networks ranging from selfish to altruistic. Our results show that three distinct strategies arise depending on the weathering rate, producing resource collection networks that are competitive, cooperative, or absent.

Introduction

Organisms undergo evolution through selective pressures from their environment, where individuals with better-suited traits leave more offspring. However, organisms can also modify their environment, altering their own and others' fitness through niche construction (Odling-Smee et al., 2003). These modified environments can persist across generations, transmitting changes in natural selection pressures to descendants - a process called ecological inheritance (Odling-Smee et al., 2003). These concepts reveal biological evolution as a complex process involving dynamic interactions between organisms and their shared environment.

Of particular interest is the relationship between niche construction and complex, large-scale cooperation, as seen in humans or social organisms. Lehmann analyzed the evolution of altruistic behavior in situations where constructed niches are inherited by future generations using a mathematical model. Traditional sociobiology held that limited dispersal creates competition among relatives, offsetting the benefits of altruistic behavior. However, he theoretically demonstrated that niche construction behaviors that posthumously improve the fitness of future related generations can decouple this competition-benefit offset relationship, thereby promoting the evolution of altruistic behavior (Lehmann, 2007). Furthermore, Laland et al. discussed how niche construction affects interactions between organisms. They proposed that when one organism's niche-constructing activities incidentally benefit others, this can develop into complementary cooperative relationships. Such interactions can provide a foundation for cooperation between unrelated individuals. These mutually beneficial relationships are considered evolutionarily more stable than purely altruistic interactions (Laland et al., 2000). These discussions suggest the existence of a complex relationship between niche construction and the evolution of altruism, highlighting the importance of demonstrating evolutionary scenarios for how complex and large-scale altruistic niche construction evolves, yielding complex interactions among multiple organisms across diverse spatiotemporal scales (Coninx, 2023).

Why do some species evolve large-scale cooperative niche construction, while others do not? Human evolution exemplifies these dynamics through extensive environmental modifications-agriculture, technology, and social institutions—that create stable niches persisting across generations via ecological and cultural inheritance (Boyd and Richerson, 1985; Laland et al., 2000). Human societies exhibit complex resource redistribution networks resembling cooperative structures in social insects (Tomasello, 2009), yet the evolutionary mechanisms underlying such resource-redistributive niche construction remain poorly understood (Henrich, 2016). This gap motivates evolutionary models that can capture how interconnected niche construction behaviors collectively transform resource distribution and foster stable cooperation across generations.

We aim to clarify how the characteristics of ecological inheritance affect this phenomenon. Related studies have examined evolution of cooperation and spatial niche construction, such as pay-off modification or limitation of game opportunities with neighbors, in spatial game-theoretical models (Suzuki and Arita, 2006; Kojima et al., 2014). Nisioti and MoulinFrier discussed mutual interactions between spatial evolutionary dynamics of niche-constructing populations and their niche dynamics in diverse multi-niche environments (Nisioti and Moulin-Frier, 2023). Chiba et al. demonstrated the evolution and ecological inheritance of complex niche constructing structures in 2D physical simulations (Chiba et al., 2020). However, how chains of niche-constructing behaviors collectively create cooperative resource networks across generations remains unexplored.

In this study, we construct an evolutionary model of resource-redistributing niche construction in a two-dimensional grid environment. Each cell contains resources and may be inhabited by agents who consume these resources for survival, reproduction, and niche construction activities. The order of these activities is represented by their genotypes and evolves. The core mechanism of niche construction is represented by pipes that transfer resources between adjacent cells. These pipes persist over multiple generations but gradually decay through a process called weathering, implementing ecological inheritance. Our model allows for complex network structures of resource transfer to emerge when multiple pipes are combined, enabling resource concentration across larger areas. However, these networks are vulnerable to disruption if key connections are lost. This generalizes both selfish and potentially altruistic niche construction, as an agent's niche construction can have positive or negative effects on its own behavior or the behavior of others, including its offspring. For example, cooperative niche construction, such as that performed by humans and ants, is represented as installing pipes that provide resources to others. Niche construction that suppresses the growth of competitors, such as that performed by some plants, is represented as installing pipes that take resources away from others.

Using this model, we show that three different strategies emerge depending on the weathering rate. In particular, we show that resource collection networks can be created through niche construction, and that the weathering rate affects whether the network is competitive or cooperative.

Model

Field

The field is a two-dimensional grid space with a toroidal structure of height H and width W. Multiple agents populate the field, with each agent occupying a cell, and several agents may coexist within the same cell. Pipes are placed in cells according to the activities of agents. Each cell $(x,\ y)$ maintains its resource quantity $R_{x,y}$, which increases or decreases based on agent activities and pipes. The passage of time is represented by discrete steps, and each agent performs one action in each step.

Figure 1 shows (a) a simple example of the genome and behavior of an agent (explained later) and (b) the whole state of the field. In Figure 1(b) (left), the location and direction of the pipes are shown by arrows that are colored according to their direction. In Figure 1(b) (right), agents are colored according to the closeness of their genetic relationship, and a blue heat map shows the amount of resources of each cell.

Agent

The actions that an agent takes at each step are divided into three types: niche construction (NC), reproduction (RP), and no behavior (NB). As shown in Figure 1(a), a genome is composed of a sequence of niche construction genes (NC genes), reproduction genes (RP genes), and no behavior genes (NB genes) that correspond to each type of action. After being placed on the field, each agent executes actions corresponding to genes in its genome sequentially, one gene per timestep, from beginning to end. Upon reaching the end of the genome, the agent loops back to the beginning and continues execution. In Figure 1(a), the agent performs NC in the first step, NC again in the second step, and RP in the third step. When they take an action, an amount of resources corresponding to the type of action （R_{NC}, R_{RP}, R_{NB}） is consumed from the cell they inhabit. When an agent takes action that would cause cell resources to go 0 or less, cell resources will go to 0, and the agent dies and is removed from the field.

NC genes contain relative position and direction variables. When executed, they install a pipe with the specified direction at the relative position. The relative position is expressed in Cartesian coordinates, such as $(3,\ 3)$, that fit within L_{NC} with Chebyshev distance. The direction is a variable that determines the destination of the pipe's resources and is expressed as a Cartesian coordinate that indicates one of the eight adjacent cells, such as $(1,\ 0)$ or $(-1,\ -1)$, and resources are transferred from the placement location to the cell in this direction. Multiple pipes with different directions can coexist in the same cell. When installing a pipe with an existing direction, the old pipe is replaced with a new one.

In the first step (top) in Figure 1(a), the NC action with direction $(1,\ 0)$ and relative position $(-1,\ 0)$ installs a right-facing pipe to the left. In this example, 3 amounts of resources are consumed from the cell in which the cell itself is located because $R_{\text{NC}} = 3$. RP genes contain the relative position for offspring placement. Offspring inherit their parents' genome, with occasional mutations. The relative position is expressed in Cartesian coordinates, such as $(1,\ 1)$, which fit within L_{RP} using the Chebyshev distance.

In the third step (bottom) in Figure 1(a), reproduction at relative position $(1,\ -1)$ creates a new agent southeastward. This consumes 20 amounts of resources because $R_{\text{RP}} = 20$, but pipe-mediated transfer of resources reduces the net decrease. The NB gene merely consumes resources, with the amount specified as R_{NB}, and does nothing else.

Mutations occur probabilistically through three mechanisms: each existing gene may be modified with probability P_{modify} or deleted with probability P_{delete}, while between any two consecutive genes, new gene insertion occurs with probability P_{insert}.

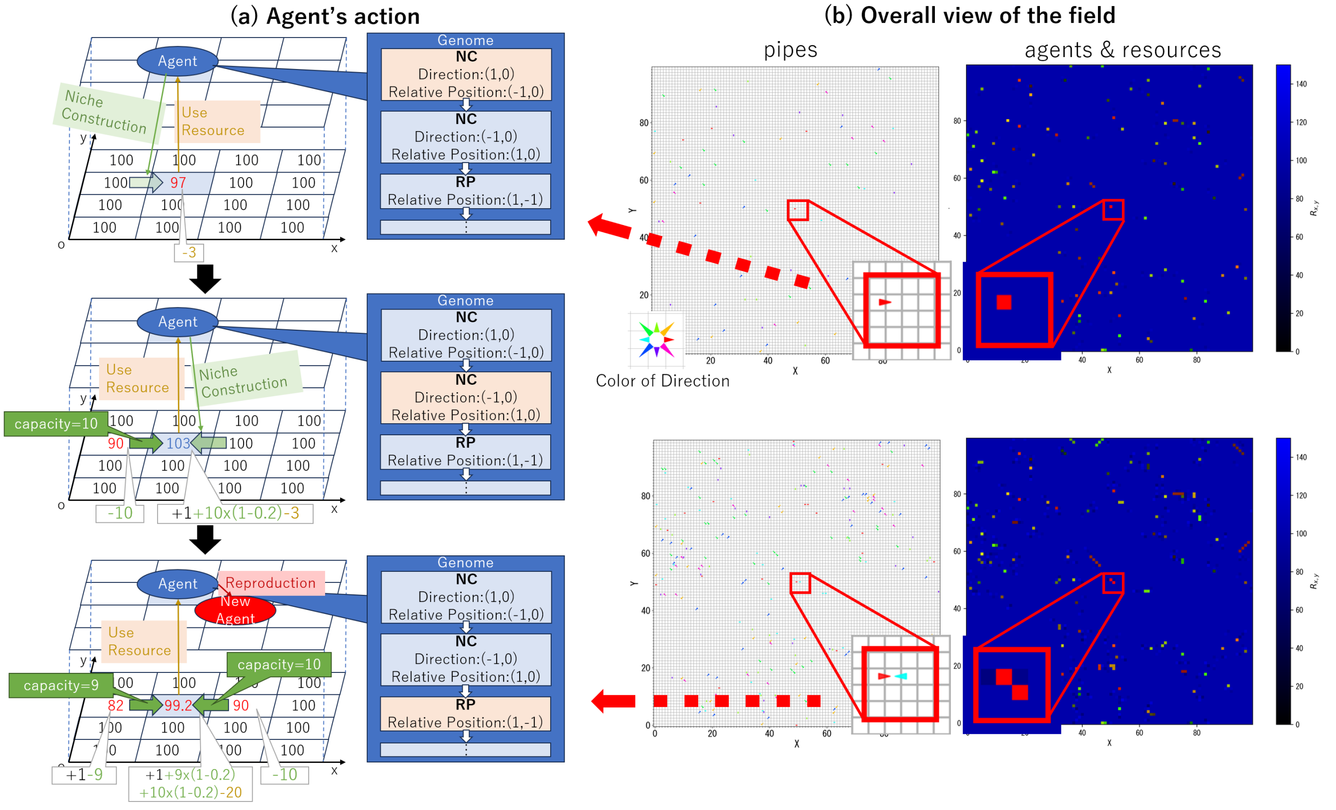

Figure 1: A simple example of the genome and behavior of an agent.

The gene to be modified undergoes complete variable randomization. New gene types follow the ratio RP gene : NC gene : NB gene = 1 : 8 : 1 (accounting for 8 possible NC directions). The directions and relative positions are chosen randomly with equal probability for all candidates. Insertions follow the same probabilities.

Reproduction will also occur even if an agent is already present in the location where an agent is to be placed, resulting in multiple agents in the same cell and the resources of that cell being consumed by the multiple agents per step.

Resource Dynamics

The resource amount of each cell $R_{x,y}$ changes through three mechanisms: natural recovery, resource transfer via pipes, and consumption by agents.

The resource amount $R_{x,y}(t+1)$ at the next timestep $t+1$ is given by:

$$\begin{aligned} R_{x,y}(t+1) &= R_{x,y}(t) + \Delta R_{\text{natural},x,y}(t) \\ &- \sum_{p \in \mathcal{P}_{\text{out},x,y}(t)} \Delta R_{\text{out},p}(t) + \sum_{p \in \mathcal{P}_{\text{in},x,y}(t)} \Delta R_{\text{in},p}(t) \\ &- \sum_{a \in \mathcal{A}_{x,y}(t)} \Delta R_{\text{consumption},a}(t). \end{aligned} \tag{1}$$

This equation shows that the amount of resources in each cell ($R_{x,y}$) increases due to natural recovery ($\Delta R_{\text{natural},x,y}(t)$), and increases or decreases due to the sum of the outflow of resources ($\Delta R_{\text{out},p}(t)$) caused by each pipe ($\mathcal{P}_{\text{out}}(x,y)$ leaving the target cell $(x,\ y)$ and the sum of the inflow of resources ($\Delta R_{\text{in},p}(t)$) caused by each pipe ($\mathcal{P}_{\text{in}}(x,y)$) into the target cell $(x,\ y)$. The amount ($\Delta R_{\text{consumption},a}(t)$) corresponding to the type of action performed by the agents ($\mathcal{A}_{x,y}(t)$) on the focal cell is consumed.

Specifically, at each step, the experiment first calculates $\Delta R_{\text{natural},x,y}(t)$. Then, for every pipe p, it computes $\Delta R_{\text{out},p}(t)$, $\Delta R_{\text{in},p}(t)$. After these resource changes, agents take actions and are subject to mortality checks.

$\Delta R_{\text{natural},x,y}(t)$ is calculated based on the value of $R_{x,y}$ at this step. If $R_{x,y}$ is below the upper recovery limit R_{limit}, 1 is added, otherwise 0 is set:

$$\Delta R_{\text{natural},x,y}(t) = \begin{cases} 1 & \text{if } R_{x,y}(t) < R_{\text{limit}} \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

In Figure 1(a), $R_{\text{limit}} = 100$, and the black numbers in the box extending from the cells show the $\Delta R_{\text{natural},x,y}(t)$ of each cell. This expresses the homeostasis of the environment, where there is a certain amount of resources to be recovered.

Each pipe p has a capacity $C_p(t)$, which indicates the maximum amount of transferable resources. The pipe p starts functioning from the next step after the Agent takes the Action to install it, and C_p at this step is always C_{init} throughout the experiment.

The outflow basically coincides with $C_p(t)$. However, if the sum of the outflows from cells $(x,\ y)$ exceeds the sum of $R_{x,y}$ and $\Delta R_{\text{natural},x,y}$, the outflow is adjusted so that $R_{x,y}$ does not become negative:

$$\Delta R_{\text{out},p}(t) = \begin{cases} C_p(t) & \text{if } S_{\text{total}} \leq R_{\text{current}} \\ \dfrac{R_{\text{current}}}{S_{\text{total}}} C_p(t) & \text{otherwise,} \end{cases} \tag{3}$$

where

$$S_{\text{total}} = \sum_{q \in \mathcal{P}_{\text{out}}(x,y)} C_q(t),$$
$$R_{\text{current}} = R_{x,y}(t) + \Delta R_{\text{natural},x,y}(t).$$

The inflow amount equals the outflow amount minus a loss rate η:

$$\Delta R_{\text{in},p}(t) = (1-\eta)\Delta R_{\text{out},p}(t). \tag{4}$$

This expresses the inherent negative effect that niche construction has on the environment due to the loss of resources through the transfer process.

In Figure 1(a), $C_{\text{init}} = 10$ and $\eta = 0.2$ are set, and the green numbers in the boxes extending from the cells show the inflow and outflow amounts of each cell. This inflow may exceed the natural recovery amount, allowing niche-constructed cells to maintain resource levels that are unattainable without niche construction, thereby providing resident agents with more opportunities for reproduction and niche construction.

The pipe capacity C_p decreases by a weathering rate γ each timestep:

$$C_p(t+1) = (1-\gamma)C_p(t). \tag{5}$$

γ is an important parameter that indicates the degree of ecological inheritance. A high value of γ corresponds to a shorter pipe lifespan, representing a fragile and difficult-to-inherit niche structure, such as a spider web. Conversely, a low value of γ corresponds to a longer pipe lifespan, representing a robust and easier-to-inherit niche structure, such as an anthill. No operations are performed to remove pipes even if the capacity becomes low.

In Figure 1, $\gamma = 0.1$ is set, and the capacity of each pipe is written in the green speech bubble extending from the pipe.

Results

All experiments begin with all cells containing R_{init} resources and no pipes installed, with N_{init} agents having random genes placed at random positions. We assume that the genome length of the initial population is G_{init}. Each gene is initialized randomly following the probability ratio RP gene : NC gene : NB gene = 1 : 8 : 1. An experiment continues executing timesteps until reaching the predetermined terminal timestep T.

We conducted experiments with the following parameter settings: $H = 100; W = 100; R_{\text{init}} = 100; N_{\text{init}} = 100; L_{\text{NC}} = 3; L_{\text{RP}} = 1; R_{\text{NC}} = 3; R_{\text{RP}} = 20; R_{\text{NB}} = 2; R_{\text{limit}} = 100; C_{\text{init}} = 10; P_{\text{modify}} = 0.0005; P_{\text{insert}} = 0.0005; P_{\text{delete}} = 0.0005; G_{\text{init}} = 10; T = 100{,}000; \eta = 0.2$.

To investigate the effect of the degree of ecological inheritance on evolutionary dynamics, we performed 20 experiments for each of nine settings of weathering rate γ, with intervals of 0.1 from 0.1 to 0.9. The codes and data, including videos showcasing typical dynamics observed in different experimental conditions, are available online[1].

Overall Trends

Figure 2 shows effects of the weathering rate γ on several metrics representing the state of population at the last time step: (a) population size, (b) average age, (c) average resource amount of each grid (R_{xy}), (d) average capacity of pipes, and (e) average proportion of the gene type in each genome. Triangles indicate mean values, with outliers defined as values beyond 1.5 times the interquartile range (IQR) (either below Q1 - 1.5 × IQR or above Q3 + 1.5 × IQR).

Note that we introduced two additional metrics to evaluate long-term system dynamics: "Change in average age" and "Change in average $R_{x,y}$" which measure their mean changes from timestep 90,000 to the end of the simulation, while the other metrics had already converged to stable values during this period.

The results revealed three distinct behavioral strategies that emerged based on the weathering rate (γ) values: At high weathering rates ($\gamma = 0.6 - 0.9$), the populations had genomes with a higher proportion of reproduction genes (approximately $25 - 40\%$ of genome composition), while pipe capacities throughout the environment remained consistently low (near zero in many cases). The agent's lifetime was very short, lasting only a few time steps (4 time steps or less in all but one trial when $\gamma = 0.9$), and the environment supported only small total populations (averaging around 900 agents) with limited available resources.

At $(x,\ y)$ weathering rates ($\gamma = 0.3 - 0.5$), we observed the largest agent populations of any strategy (reaching approximately 1,200-1,400 agents). Genome composition in this strategy showed dominance of niche construction genes (around 65-85%). Agents in these environments showed intermediate values for age (around 6,000-7,000 timesteps at $\gamma = 0.3$), resource levels(approximately 400-500), and pipe

---

[1] https://doi.org/10.6084/m9.figshare.30017092

capacities (approximately 0.3-0.4) compared to the other strategies.

At low weathering rates ($\gamma = 0.1 - 0.2$), agents achieved the highest average lifespans (exceeding 7,500 timesteps at $\gamma = 0.1$; exceeding 14,000 timesteps at $\gamma = 0.2$), resource levels (approximately 1,000), and pipe capacities (0.6-0.8). Despite these advantages, these environments supported smaller total populations (approximately 1,000-1,100 agents) than those observed with the $(x,\ y)$ γ cases.

When the number of individuals was compared using the Wilcoxon rank-sum test as an indicator of the structure of the entire population, there was a significant difference between typical settings ($\gamma = 0.1, 0.3, 0.9$) ($p < 0.001$). When the composition ratio of each gene was compared as an indicator of evolutionary trends, there was a significant difference for the RP and NC genes that determine the behavior of individuals ($p < 0.05$ for NB between 0.1 and 0.3, $p < 0.001$ for the other cases), but there was no significance for the NB gene ($p > 0.1$).

These distinct strategies demonstrate how the degree of ecological inheritance fundamentally shapes the evolution of population characteristics through niche construction.

Based on these findings, we focus on three representative cases for detailed analysis: $\gamma = 0.9$ (high weathering rate), $\gamma = 0.3$ ($(x,\ y)$), and $\gamma = 0.1$ (low).

High Weathering Rate Experiment ($\gamma = 0.9$) : Emergence of Migration Strategy

We begin by analyzing the case with high weathering rate ($\gamma = 0.9$). We observed the emergence of actively migrating groups without niche construction, referred to as the migration strategy. Figure 3 displays the environmental dynamics and most prevalent genome from a representative experimental trial, where agents achieved an average lifespan of only 2.26 timesteps.

Figure 3(a) shows pipe configurations, agent/resource distributions, and zoomed-in views at timesteps 99,980, 99,990, and 100,000. Following the same conventions as Figure 1, pipes (left) are represented by color-coded directional arrows (while not clearly observable because of the small number of pipes in this case). Agents (center and right) are colored to represent different genotypes, with resource levels of cells shown in blue. The rightmost panel highlights a representative cluster of agents with the prevalent (the most frequent) genome in the population at the last timestep. In general, when γ was high, linear groups were formed and they were moving in one direction, colliding with each other, as illustrated in the zoomed-in views.

We investigate the behavior of this prevalent genome in detail to understand its emergent dynamics. Figure 3(b) illustrates the visualization of a single agent's behavior with the most prevalent genome, placed at the center of a vacant space. The numbers represent the order of execution of the actions in the genome. The arrows indicate pipe placement (direction and relative position from the agent), red dots represent reproduction sites.

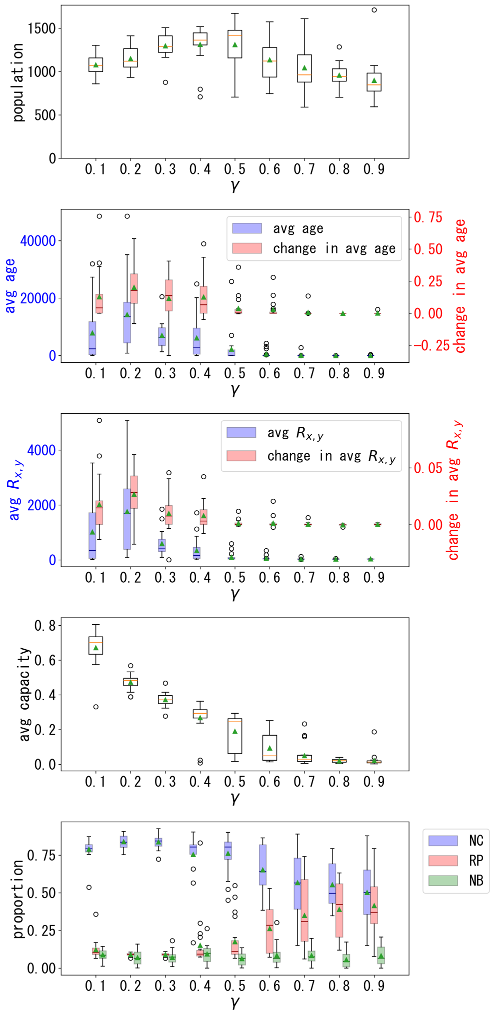

Figure 2: Relationships between γ and various metrics at the final timestep. From top to bottom: (a) agent population, (b) average age, (c) resource levels, (d) pipe capacity, and (e) genome composition.

As in Figure 3(b), the genome's initial actions, such as the first and second, were primarily reproductive behaviors, and niche construction was not common. Thus, the agents left offspring in the direction of the first reproduction and died quickly because of the lack of resources due to the large cost for reproduction, which repeatedly occurred (e.g., the green arrow direction in the zoomed-in view), and the formed group continues to move in this direction. Additionally, reproduction by the second and subsequent actions in the genome was occasionally performed, allowing the new linear group to spread in this direction alongside the original one, thereby causing the whole group to move towards the direction of this reproduction behavior (i.e., the yellow arrow direction).

These dynamics demonstrate that niche construction has a negligible impact on population behavior at high weathering rates. Instead, agents evolve reproduction-prioritizing strategies, relying on habitat shifting rather than resource gathering. This adaptation emerges because rapid pipe degradation ($\gamma = 0.9$) makes resource gathering via niche construction inefficient compared to acquisition based on generation changes.

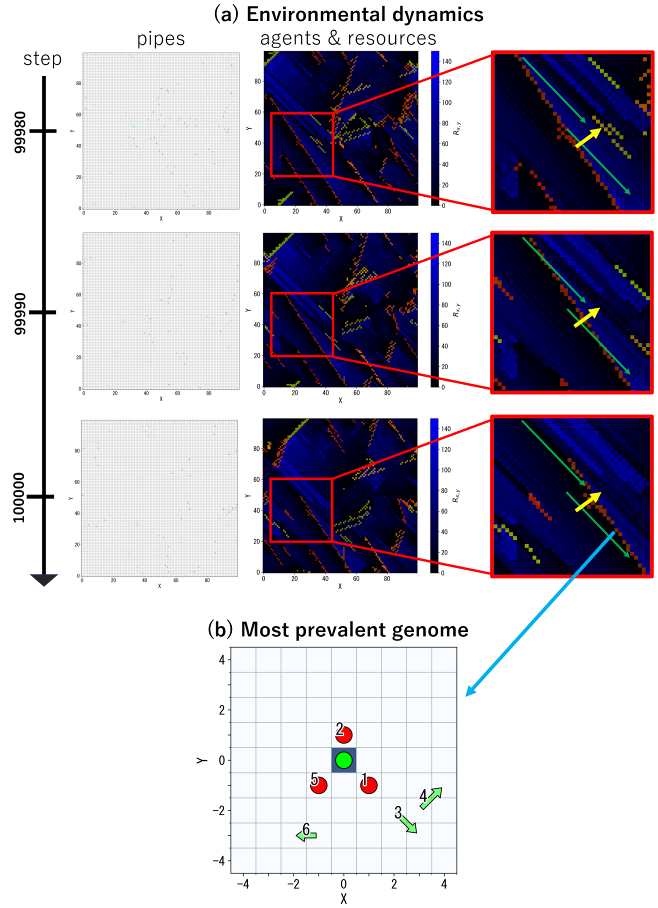

Figure 3: Environmental dynamics and most prevalent genome at $\gamma = 0.3$ (migration strategy). (a) Pipes (left, colored arrows) and agents/resources (right, heat map) at three time points. (b) Prevalent genome behavior: pipe placements (green arrows) and reproduction sites (red dots).

Medium Weathering Rate Experiment ($\gamma = 0.3$) : Competitive Niche Construction Strategy

Next, we analyze the case with $\gamma = 0.3$. We observed the emergence of resource-gathering networks composed of multiple pipes for actively gathering the niche-constructer's own resources, referred to as the competitive niche construction strategy. Figure 4 shows the environmental dynamics and the most prevalent genome in a typical trial of $\gamma = 0.3$. Unlike the case of $\gamma = 0.9$, a complex arrangement of agents and pipes was observed, with agents densely populating the cells to form diagonal structures, which remained significantly stable throughout the trial. The average age was 4,213.82, which is much longer than that in the previous case.

Figure 4(b) illustrates the behavior of the most prevalent genome, corresponding to the orange agents centered in the zoomed-in image. It is worth noting that this agent created a complex network structure of many pipes, which enabled it to gather resources from neighboring cells effectively to the agent's cell. We define the resource-gathering network for a focal agent on a given pipe distribution as the set of cells that can transport resources to the agent's current cell through the existing pipe network, including indirect transport through chains of multiple pipes. For example, the resource-gathering network of the agent in Figure 4(b) is represented as the colored cells, from which resources can be delivered to the focal agent through the pipe network. Additionally, we define the network capacity as the weighted sum of cells in the network, where the weight of each cell is calculated as one divided by the number of overlaps when the cell is shared with resource-gathering networks of other agents in the field. The capacity of the network in Figure 4(b) is 9, which means the agent can construct the high-capacity network if there exist no other agents.

However, this effective network brings about competition among networks of other agents over the trial. Figure 4(c) shows the typical arrangement of agents and pipes on the cells of the zoomed-in view in Figure 4(a). We focused on and visualized the pipes placed by the existing agents during the timesteps of the length of the prevalent genome, which is an approximation of the constructed pipe structures in the trial. Agents are assigned individual colors for clarity, and pipes are colored by the color of the agent they are placed in. The colored cells represent the resource-gathering network of the center agent with the prevalent genome, and their color reflects the weight of their capacity. It should be noted that the capacity of this network was 7.18, which is smaller than that in Figure 4(b), indicating that there exist strong competitive relationships among neighboring agents due to the overlaps of their resource networks. Such competitions were mitigated to some extent by reproductive strategies. Their reproduction direction was limited to a diagonal location; agents did not live in adjacent cells above, below, left, or right, and the agent density decreased.

Competitive niche construction strategy allows for more stable reproduction, but also leads to disorderly and excessive population density. As a result, although the population size increases, the average age is likely to be somewhat low due to resource shortages.

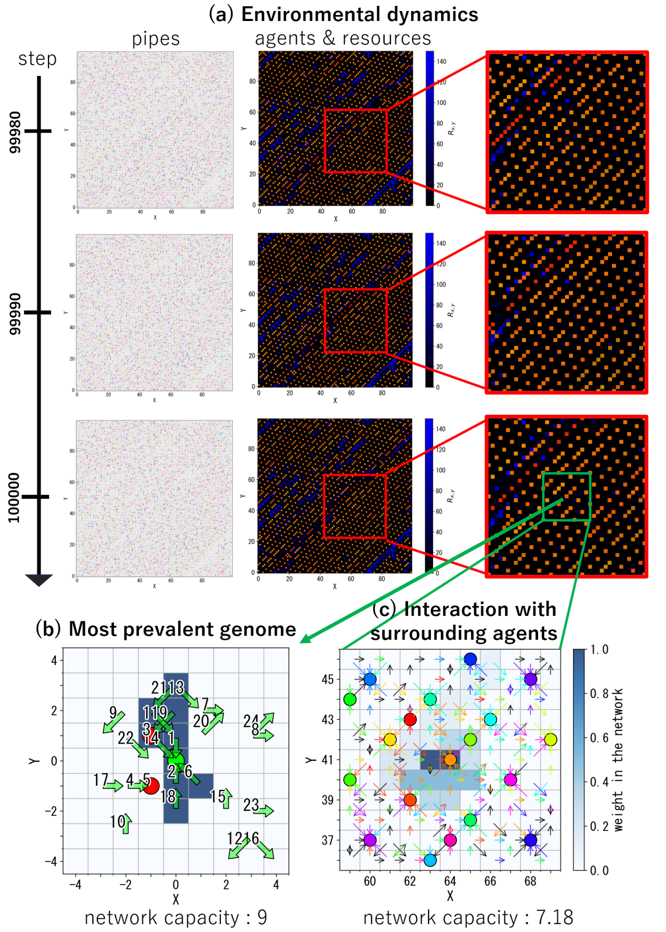

Figure 4: Environmental dynamics and most prevalent genome at $\gamma = 0.3$ (competitive niche construction strategy). (a-b) Same as Figure 3. (c) Agent interactions: colored circles: agents, pipe colors match agent colors, colored cells: resource-gathering network for focal agent.

Low Weathering Rate Experiment ($\gamma = 0.1$)

Finally, we analyze the case of $\gamma = 0.1$. We observed that niche-constructing agents collectively and cooperatively created resource networks that prioritized giving resources average, but in this study, we chose the trial with a medium average age as a representative of the results. The average age was 11,328.49, which is even higher than $\gamma = 0.3$.

When γ was low, agents settled at greater intervals than when γ was intermediate. This indicates that their niche constructing behavior adaptively adjusted their habitat to an appropriate density. Although the direction of reproduction was diagonal, they sometimes formed structures arranged vertically or horizontally, as illustrated in Figure 5(a). This indicates that the location where they could leave their offspring changed depending on the environment around the parents' habitat.

The capacity of the network in Figure 5(b), which exhibits the behavior of the prevalent genome in a vacant space, is 7. This means that in the absence of other agents, the agent can build a network with a smaller capacity than when γ was medium. However, this network has a higher capacity through the cooperation of other agents during trials. Figure 5(c) shows a typical arrangement of agents and pipes in a cell, in a zoomed-in view of Figure 5(a), similar to Figure 4(c). The capacity of the network of the central agent was 10.83, which is larger than Figure 5(b). This is because the agents have a high degree of habitat control through niche construction and build a network that collectively and effectively utilizes each other's resource networks.

More specifically, in the genome shown in Figure 5(b), the second, third, seventh, and ninth actions, which are performed early on, move resources away from the agent. The action of moving resources to the cell inhabited by the agent is also very late, at the 11th and 13th steps. In such cases, only the agent that has received the resources via pipes constructed by other agents can survive. Therefore, it is possible to prevent agents from living in a less adaptive location by interfering with the surrounding agents. In the example shown in Figure 5, the cell two cells to the left of the one where a grandchild is likely to be born has a lot of resources gathered by the niche construction of the second and 19th. The agent can continue to survive, but the cell where the direct child is born cannot survive for a long time because its resources are taken by the agent itself and its grandchild. Agents living in well-niche-constructed habitats make effective use of each other's pipes. The network shown in Figure 5(c) contains many pipes of purple individuals that correspond to the grandchildren of the agent in question and red individuals that correspond to the grandparents. Furthermore, cooperative behavior was also observed with agents with weak genetic ties. The yellow agent four cells above helped the central agent gather resources from the cell above by the niche construction of the third, and the magenta agent living in the upper right helped the agent gather resources from the cell in the upper left by the 7th niche-constructing behavior. This shows that cooperation occurs even with agents with weak genetic ties through pipes very far away from the agent itself.

When γ is low, niche construction has a strong influence on environmental resource dynamics. Therefore, if an organism can live in a place where it can receive cooperation, it can at least leave offspring. This is expected to be the reason that this cooperative niche construction strategy evolved. Notably, this strategy resulted in a high average age. On the other hand, a competitive niche construction strategy, such as that observed when γ was intermediate, would not spread because of the strong competition for resources.

Lower mean ages and resource levels were observed at $\gamma = 0.1$ compared to $\gamma = 0.2$ in Figure 2. When weathering is very slow, before advanced networks are established, disorganized pipes maintain high capacity, displacing resources and causing large volume losses. This leads to resource depletion and increased mortality. Paradoxically, niche construction continues to be highly selected for, even in such resource-scarce conditions, because its accumulation efficiency exceeds other options. As a result, a self-reinforcing cycle of high pipe capacity is formed, exacerbating resource depletion.

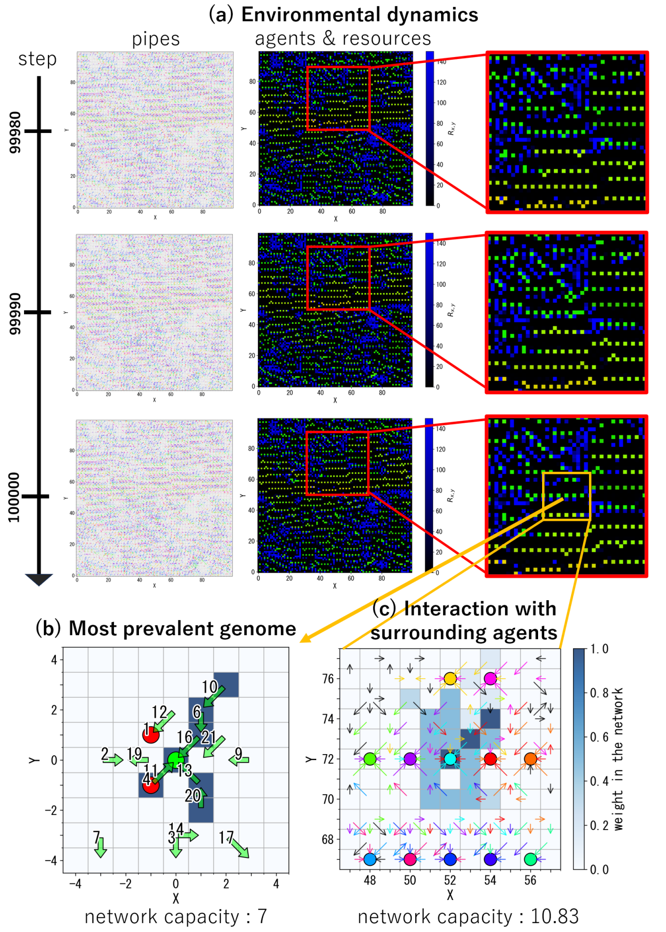

Figure 5: Environmental dynamics and most prevalent genome at $\gamma = 0.1$ (cooperative niche construction strategy). Format follows Figure 4.

Cooperation Metrics

The difference in the emerging niche-constructing dynamics between when γ was intermediate and when γ was low is expected to be due to the competitive and cooperative nature of niche construction. To quantitatively evaluate this, we define a cooperation index C as a rough estimate of the difference between the resource-gathering capacity of agents when considering surrounding agents' influence (as shown in Figure 4(c) and 5(c)), and those without considering others' effects (as shown in Figure 4(b) and 5(b)). If this value is positive, it indicates that the surrounding agents are helping the agent to gather resources, and if it is negative, it indicates that they are hindering gathering. In the case of Figure 4, $C = 7.18 - 9 = -1.82$, and in the case of Figure 5, $C = 10.83 - 7 = 3.83$.

Figure 6 demonstrates the relationship between γ and C for prevalent genomes. High γ values (0.6-0.9) yield $C \approx 0$ as rapid pipe weathering prevented sustained interactions. Medium γ values (0.3-0.5) produce negative C values, indicating competitive systems where agents' pipe networks mutually interfere. Low γ (0.1-0.2) yielded positive or relatively higher C compared to medium γ values, proving that slow weathering enables evolution of cooperative systems where persistent pipe networks create stable mutualisms.

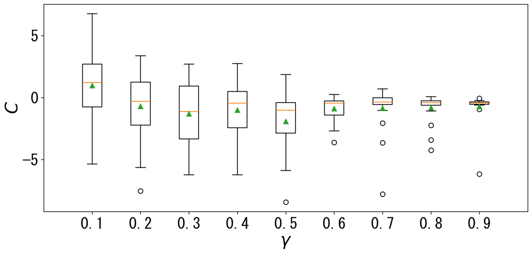

Figure 6: Cooperation index (C) versus weathering rate (γ) for dominant genomes.

Conclusion

We developed an evolutionary model of niche construction that alters the distribution of resources across a field, and analyzed how different degrees of ecological inheritance (weathering rates) led to statistically distinct evolving strategies and population structures.

Our findings reveal three evolutionary strategies corresponding to different niche durability levels. While our model is highly abstract and not human-specific, potential correspondences with human evolution offer instructive insights. Low niche durability promotes migration strategies, conceptually paralleling early human dispersal patterns (Kelly, 2013). Medium durability fosters competitive niche construction, analogous to territorial behaviors in early agricultural societies (Diamond, 1997). High durability enables cooperative niche construction, corresponding to stable cultural institutions and cumulative technologies in modern societies (Boyd and Richerson, 1985; Henrich, 2016). This pattern indicates that durable niche construction could potentially facilitate the transition from competitive to cooperative strategies, though the causal mechanisms remain to be fully elucidated.

Future work includes varying fixed parameters, enabling adaptive behaviors such as division of labor, and allowing weathering rates to evolve to reveal new cooperative and strategic dynamics in resource-redistributive niche construction.

References

Boyd, R. and Richerson, P. J. (1985). *Culture and the evolutionary process*. University of Chicago Press.

Chiba, N., Suzuki, R., and Arita, T. (2020). Evolution of complex niche-constructing behaviors and ecological inheritance of adaptive structures in a physically grounded environment. *Frontiers in Robotics and AI*, 7:45.

Coninx, S. (2023). The dark side of niche construction. *Philosophical Studies*, 180(10):3003–3030.

Diamond, J. (1997). *Guns, Germs, and Steel: The Fates of Human Societies*. W. W. Norton & Company.

Henrich, J. (2016). *The secret of our success: How culture is driving human evolution, domesticating our species, and making us smarter*. Princeton University Press.

Kelly, R. L. (2013). *The lifeways of hunter-gatherers: the foraging spectrum*. Cambridge University Press.

Kojima, T., Suzuki, R., and Arita, T. (2014). Effects of ecological inheritance on coevolution of cooperative behaviors and physically niche constructing behaviors. *Journal of Advanced Computational Intelligence and Intelligent Informatics*, 18(3):391–400.

Laland, K. N., Odling-Smee, F. J., and Feldman, M. W. (2000). Niche construction, biological evolution, and cultural change. *Behavioral and brain sciences*, 23(1):131–146.

Lehmann, L. (2007). The evolution of trans-generational altruism: kin selection meets niche construction. *Journal of Evolutionary Biology*, 20(1):181–189.

Nisioti, E. and Moulin-Frier, C. (2023). Dynamics of niche construction in adaptable populations evolving in diverse environments. In *ALIFE 2023: Ghost in the Machine: Proceedings of the 2023 Artificial Life Conference*, pages isal_a_00668,63. MIT Press.

Odling-Smee, F. J., Laland, K. N., and Feldman, M. W. (2003). *Niche construction: the neglected process in evolution (MPB-37)*. Princeton University Press.

Suzuki, R. and Arita, T. (2006). How spatial locality can affect the evolution of niche construction. In *Proceedings of Artificial Life X*, pages 452–458.

Tomasello, M. (2009). *Why we cooperate*. MIT press.