

# Collective Dynamics and Homeostatic Emergence in Complex Adaptive Ecosystem

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## Abstract

We investigate the behaviour of the daisyworld model on an adaptive network, comparing it to previous studies on a fixed topology grid, and a fixed small-world (Newman-Watts (NW)) network. The adaptive networks eventually generate topologies with small-world effect behaving similarly to the NW model – and radically different from the grid world. Under the same parameter settings, static but complex patterns emerge in the grid world. In the NW model, we see the emergence of completely coherent periodic dominance. In the adaptive-topology world, the systems may transit through varied behaviours, but can self-organise to a small-world network structure with similar cyclic behaviour to the NW model.

## Introduction

In this paper, we examine connectivity changes in a complex adaptive ecosystem based on the daisyworld model, combining coupled map lattice (CML) and complex adaptive network models. Daisyworld, proposed by Watson and Lovelock (1983), is a simple mathematical system demonstrating planetary homeostasis – self-regulation of the environment by biota and self-sustainability of life through interaction with the environment. Daisyworld topologies in the literature are static, with only local connections (Wood et al., 2008). In our previous work (Punithan et al., 2011; Punithan and McKay, 2013), we have investigated ecological homeostasis in preconstructed static topologies with local and non-local long range couplings – small-world networks. But complex networks in nature and society are adaptive, in that they exhibit feedback between the local dynamics of nodes (state) and the evolution of the topological structure (Gross and Blasius, 2008; Gross and Sayama, 2009). Examples include genetic, neural, immunity, ecological, economic and social networks, complex game interactions etc.

The topology of our ecosystem evolves in response to local habitat states, and the evolved topology in turn impacts the habitat states. Our adaptive and self-maintaining ecosystem, based on CML consists of a set of diffusively coupled habitats incorporating logistic growth of life with bi-directional biota-environment influences. Thus our ecosystem incorporates three kinds of feedback:

1. Life-environment feedback via the daisyworld model
2. State-topology feedback via an adaptive network model
3. Density-growth feedback via a logistic growth model

The topology of the our ecosystem evolves with a simple local rule – a frozen habitat is reciprocally linked to an active habitat – and self-organises to complex topologies with small-world effect. In this paper, we focus on the emergent collective phenomena and properties that arise in egalitarian small-world ecosystems, constructed from a large number of interacting adaptively linked habitats.

## Background

Our model has three feedback loops determining its dynamics. We next detail the relevant background.

**Daisyworld (homeostatic self-regulation of the environment by the biota)** Daisyworld (Watson and Lovelock, 1983) is an imaginary planet where only two types of species live – black and white daisies. These biotic components interact stigmergically via an abiotic component – temperature. The different colours of the daisies influence the albedo (reflectivity) of the planet. In the beginning, the atmosphere of the daisyworld is cooler and only black daisies thrive as they absorb all the energy. As the black daisy population expands, it warms the planet. When it is too warm for black daisies to survive, white daisies start to bloom since they reflect all the energy back into space. As the white daisy cover spreads, it cools the planet. When it is too cold for the survival of white daisies, again black daisies thrive. This endless cycle, owing to the bi-directional feedback loop between life and the environment, self-regulates the temperature and thereby allows life to persist.

**Adaptive Networks (dynamics on the network interacting with dynamics of the network)** In most real-world networks, the topology itself is a dynamical system which changes in time and in response to the dynamics of the states of the nodes (dynamics of the network). The evolved topology in turn influences the dynamics of the states of the nodes

(dynamics *on* the network), creating a feedback loop between the dynamics of the nodes and the evolution of the topology. Networks exhibiting such a feedback loop (mutual evolution of structure and state values) are called adaptive or coevolutionary networks (Gross and Blasius, 2008; Gross and Sayama, 2009). In road networks, the topology of the road influences the traffic flow, while traffic congestion influences the construction of new roads. In the vascular system, the topology of the blood vessels controls blood flow, while restrictions in blood flow influence the formation of new arteries (arteriogenesis). Numerous other examples are discussed in Gross and Blasius (2008).

**Logistic Growth Model (density-dependent growth rate)**  
The discretised logistic growth model (Verhulst model) is key to population ecology.

$$P_{(t+1)} = P_t \left[ 1 + r \left( 1 - \frac{P_t}{\kappa} \right) \right]; \quad r > 0, \kappa > 0 \quad (1)$$

where  $P \in [0, \kappa]$  is the population size (at times  $t$  and  $t + 1$ ),  $r$  is the intrinsic growth rate (bifurcation parameter),  $\kappa$  is the carrying capacity (maximum sustainable population beyond which  $P$  cannot increase). The parameter  $r$  amplifies population growth and the component  $[1 - \frac{P_t}{\kappa}]$  dampens the growth due to over crowding. Thus population density self-regulates population growth rate. It is also well-known that chaos emerges from this growth model (May, 1976) in spite of the built-in regulatory mechanism.

**Coupled Map Lattice** The coupled map lattice (Kaneko, 1985, 1992; Kaneko and Tsuda, 2001) incorporates discrete time evolution (map) in a discrete space (lattice or network) as in cellular automata (CA), but takes continuous state values as in partial differential equation (PDE) models. CML is governed by the temporal nonlinear reaction (maps -  $f$ ) and the spatial diffusion (coupling -  $\epsilon$ ).

If  $f(x)$  is a reaction function of a dynamical variable ( $x$ ), the update of the variable is computed by combining that reaction with discrete Laplacian diffusion. For a regular network with Moore neighbourhoods ( $k = 8$ ), the update of  $x$  is computed as:

$$x_{(i,j,t+1)} = f \left( (1 - \epsilon)x_{(i,j,t)} + \frac{\epsilon}{8} \left[ x_{(i+1,j,t)} + x_{(i-1,j,t)} + x_{(i,j+1,t)} + x_{(i,j-1,t)} + x_{(i-1,j-1,t)} + x_{(i+1,j-1,t)} + x_{(i-1,j+1,t)} + x_{(i+1,j+1,t)} \right] \right) \quad (2)$$

where  $x_{(i,j,t)}$  is the spatio-temporal distribution of a dynamical variable,  $\epsilon \in [0, 1]$  is the coupling parameter (diffusion rate),  $k$  is the number of interacting neighbours,  $f(x'_{(i,j,t)})$  is a local non-linear function and  $x'_{(i,j,t)}$  is the value after diffusion.

Denoting the set of neighbours of  $(i, j)$  as  $\langle l, m \rangle$ , we can simplify equation 2 to:

$$x_{(i,j,t+1)} = f \left( (1 - \epsilon)x_{(i,j,t)} + \frac{\epsilon}{k} \sum_{\langle l,m \rangle}^k x_{(l,m,t)} \right) \quad (3)$$

**Small-world Phenomena** The co-occurrence of high clustering (as in regular networks) and low characteristic path length (as in random networks) define a small-world structure (Watts and Strogatz, 1998). These small-world network properties, giving rise to the well-known “six degrees of separation” phenomenon (Milgram, 1967), are quantified by two statistical measures: the clustering co-efficient (measuring local cliqui-ness)  $\mathcal{C}$ , and the characteristic path length  $\mathcal{L}$  (measuring global connectedness). Their average values  $\bar{\mathcal{C}}$  and  $\bar{\mathcal{L}}$  for a network with  $n$  nodes are defined by:

$$\bar{\mathcal{C}} = \frac{1}{n} \sum_{v=1}^n \frac{|E(\Gamma_v)|}{\binom{k_v}{2}} \quad (4)$$

where  $\Gamma_v$  is the neighbourhood of a node  $v$ ,  $|E(\Gamma_v)|$  is the number of actual links in the neighbourhood of  $v$ ,  $k_v$  is the number of nodes in the subnetwork  $\Gamma_v$  and  $\binom{k_v}{2}$  is the number of possible links in  $\Gamma_v$ ; and

$$\bar{\mathcal{L}} = \frac{1}{\binom{n}{2}} \sum_{u=1}^n \sum_{v>u}^n d_{uv} \quad (5)$$

where  $d_{uv}$  is the shortest path between a pair of nodes  $u, v$ .

**Degree Distribution** The degree of a node is the number of neighbours it is connected to. The degree distribution is defined as the normalised frequency distribution of degrees over the whole network. The degree distribution of a network is a simple property which helps to classify networks. The regular network with Moore neighbourhoods have the same degree ( $k = 8$ ) for all the nodes. The degree distribution of small-world networks ( $p$  in the small-world regime (Punithan and McKay, 2013) follows a Poisson distribution with exponential tail. Networks in which most nodes have approximately the same number of neighbours are known as “egalitarian” networks (Buchanan, 2003).

### Model

Our ecosystem is a complex dynamic system in which the continuous state habitats diffusively interact with their neighbours (coupled), evolve in discrete time (map) and are distributed on a discrete space (lattice). Initially, we construct a 2-lattice with Moore neighbourhoods and periodic boundary conditions. Each point in the lattice represents a habitat with a maximum carrying capacity of 10, 000 daisies. Each habitat in our ecosystem is a system. The elements

such as life (black and white daisies) and environment (temperature) are interconnected and interdependent via reinforcing and balancing feedback loops. At each succession of a habitat, we compute the population of black and white daisies, and the temperature, based on equation 3.

Table 1: Daisyworld Parameter Settings

Parameter	Value
Number of habitats ( $N \times N$ )	100 × 100
Heat capacity ( $C$ ) $Wm^{-2}K^{-1}$	2500
Diffusion constant ( $D_T$ ) $Wm^{-2}K^{-1}$	500
Stefan-Boltzmann constant ( $\sigma_B$ ) $E^{-8}Wm^{-2}K^{-4}$	5.67
Luminosity ( $L$ )	1
Solar Insolation ( $S$ ) $Wm^{-2}$	864.65
Noise Level ( $K$ )	0.001
Opt. temp of black daisies $T_{opt_b}$ (K)	284.5
Opt. temp of white daisies $T_{opt_w}$ (K)	306.5
Carrying capacity ( $\kappa$ )	10000
Dispersion rate of daisies ( $D_c$ )	0.2
Natural rate of increase ( $r$ )	1

**Albedo:**

The albedo ( $A$ ) at a lattice point  $(i, j)$  and at time  $(t)$  is

$$A_{(i,j,t)} = A_b(\alpha_b)_{(i,j,t)} + A_w(\alpha_w)_{(i,j,t)} + A_g(\alpha_g)_{(i,j,t)} \quad (6)$$

i.e. the average of the albedos  $A_b$  of ground covered by black daisies,  $A_w$  of ground covered by white daisies and  $A_g$  of bare ground, weighted by  $\alpha_b, \alpha_w, \alpha_g (= 1 - \alpha_w - \alpha_b) \in [0, 1]$ , the relative areas occupied by black, white daisies and bare ground at time  $t$ . We assume that  $A_w > A_g > A_b$ , with corresponding values of 0.75, 0.5, 0.25.

**Growth:**

The growth curve of daisies ( $\beta_c$ ) is an inverted parabola:

$$\beta_c(T_{(i,j,t)}) = \max \left( 1 - \left[ \frac{(T_{opt_c} - T_{(i,j,t)})^2}{17.5^2} \right], 0 \right) \quad (7)$$

$T_{(i,j,t)}$  is the local temperature and  $T_{opt_c}$  is the optimal temperature of the species. The optimal temperature of the daisies depends on their petal colour ‘c’ (phenotype). The optimal temperature for black daisies is lower than for white; the mean optimal temperature is assumed to be 295.5K.

**Temperature:**

The temperature ( $T_{(i,j,t+1)}$ ) is computed as the sum of temperature after Laplacian diffusion ( $T'_{(i,j,t)}$ ), the difference between solar absorption and heat radiation incorporating  $T'_{(i,j,t)}$ , and Gaussian white noise:

$$T_{(i,j,t+1)} = g \left( (1 - D)T_{(i,j,t)} + \frac{D}{k} \sum_{\langle l,m \rangle} T_{(l,m,t)} \right) \quad (8)$$

where  $T_{(i,j,t)}$  is local temperature,  $\langle l, m \rangle$  represents the set of neighbours of  $(i, j)$  and  $D = D_T/C$  is the thermal diffusion constant normalised by heat capacity  $C$ .  $g(T'_{(i,j,t)})$  is the temperature update function (Wood et al., 2008), in which  $T'_{(i,j,t)}$  is the temperature after diffusion:

$$g(T'_{(i,j,t)}) = T'_{(i,j,t)} + \xi + \left[ \frac{(SL(1 - A_{(i,j,t)}) - \sigma_B(T'_{(i,j,t)}))^4}{C} \right] \quad (9)$$

where  $S$  is the solar constant,  $L$  is the luminosity,  $A_{(i,j,t)}$  is the albedo,  $\sigma_B$  is the Stefan-Boltzmann constant and  $\xi$  is additive Gaussian white noise (with mean 0 and standard deviation 1.0) multiplied by the noise level (NL).

**Population size:**

The local population update depends on dispersion, density-dependant growth rate and the feedback coefficient:

$$P_{c(i,j,t+1)} = h \left( (1 - D_c)P_{c(i,j,t)} + \frac{D_c}{k} \sum_{\langle l,m \rangle} P_{c(l,m,t)} \right) \quad (10)$$

where  $P_{c(i,j,t)}$  is the population size at location  $(i, j)$  and time step  $t$ ,  $D_c$  is the fraction of the population being dispersed to its neighbours,  $c$  stands for colour of daisies and  $k$  is number of neighbours.  $h(P'_{c(i,j,t)})$  is the population growth function and  $P'_{c(i,j,t)}$  is population size after dispersion:

$$h(P'_{c(i,j,t)}) = P'_{c(i,j,t)} \left[ 1 + r \left( \beta_c(T_{(i,j,t)}) - \frac{P'_{c(i,j,t)}}{\kappa} \right) \right] \quad (11)$$

where  $r$  is population increase rate,  $\beta_c(T_{(i,j,t)})$  is the feedback due to temperature and  $\kappa$  is the carrying capacity.

**The Small-world Network Model**

Small-world networks can be modelled in various ways – Watts and Strogatz (1998) (WS) model, Newman and Watts (1999) (NW) model, etc. Although the WS model was a breakthrough in network science, it may not guarantee connectivity owing to the rewiring process – deleting connections in the underlying network may result in disjoint nodes. Hence we use the later NW model, where we only add long-range connections. For each connection in the underlying ecosystem, a new reciprocal connection is added to a randomly chosen non-local habitat with probability  $p \in [0, 1]$ . In this work, we have chosen  $p = 0.05$ , since it is in the small-world regime and has proven to have interesting dynamics (Punithan and McKay, 2013).

### Adaptive Network Model

Adaptive networks are a class of dynamical networks whose topologies and states coevolve. Dynamic Linking (DL) is the key feature of adaptive networks, and can be modelled in a number of ways:

1. Active nodes grow and inactive nodes lose links
2. Active nodes lose links and inactive nodes grow them
3. Nodes never lose links; the network evolves by either:
  - (a) Adding new links to active nodes from inactive nodes
  - (b) Adding new links to inactive nodes from active nodes
  - (c) Adding reciprocal links between active and inactive nodes

By means of DL, we model the topology of our ecosystem itself as a dynamical system, changing in time according to a simple local rule (dynamics of networks). Each habitat, representing a dynamical system (dynamics on networks), is dynamically coupled according to the evolved topology. In our ecosystem, we never remove connections between habitats; we add new reciprocal connections between frozen habitats and active habitats (i.e. method 3c). This simple rule gives rise to a complex topology.

In our model, only black and white daisies disperse via both local and long-range connections, created either statically or dynamically (by water, air, animal pollinator transport etc.), while temperature diffuses only locally.

## Experiments

### Experiment Settings

The habitats are randomly initialised with a population size in  $[0, 100]$  for both species and with the temperature in  $[280, 310]K$ . We permit both species of daisies to coexist, hence we allow an overlap of 10% in the growth response to temperature. The overlap chosen determines the optimal temperature values of daisies. The parameter and their values are described in Table 1.

We have investigated daisyworld phenomenon in three different topological scenarios:

1. We start with an ecosystem where habitats are only locally connected (regular CML with Moore neighbourhood).
2. We add random non-local links to the underlying regular lattice, which introduces small-world effects in ecosystem (Newman-Watts model in CML)
3. Each frozen node in the underlying regular lattice is dynamically and reciprocally linked to a randomly chosen active node (adaptive CML).

A node is said to be frozen when its local dynamics are static – black and white daisies maintain the same population size

for six consecutive epochs. The links added either statically (NW) or dynamically (adaptive) are reciprocal links (mutual links). We ran 25 realisations of each network model, and present a typical example of a run of each model. Scenarios 1 and 2 were previously analysed in Punithan et al. (2011) and Punithan and McKay (2013), though with different overlaps (0% and 5%) respectively.

### Visualisations

We capture snapshots from the evolution of daisyworld to inspect its spatio-temporal dynamics. Each snapshot represents the population structure of the ecosystem at the particular epoch. As it is impractical to show all the snapshots over 5,000 epochs, we plot the temporal dynamics of daisy populations and temperature at a particular habitat as well as the temporal dynamics of the average daisy populations and temperature of the whole ecosystem. These plots reflect the behaviour of the daisyworld.

In the visualisations, a habitat is shown as black if black daisies alone occupy that habitat and correspondingly for white. If both daisies coexist at a habitat but black dominates, it is shown as dark grey; if white dominates, it is presented as light grey; and if the populations are equal, it is represented as medium grey.

## Results

### I. Daisyworld with Static Local Couplings (Regular Networks)

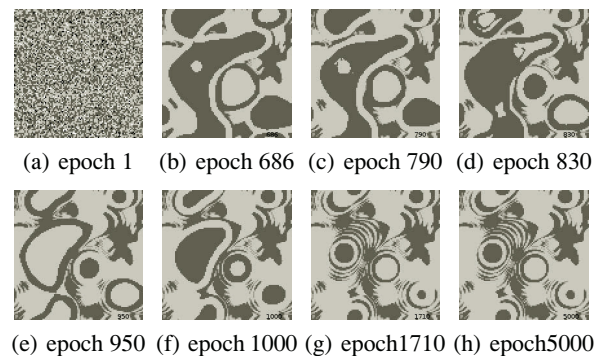
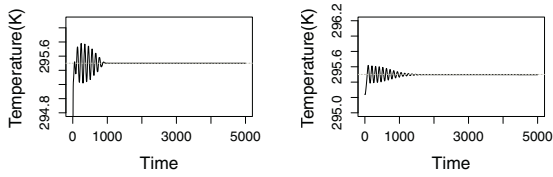


Figure 1: Regular CML:  $D = 0.2$  and  $NL = 0.001$  in 2D  $100 \times 100$

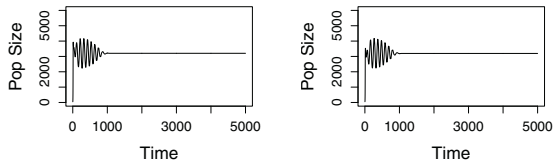
With only local couplings, we observe the formation of complex static patterns. The whole ecosystem freezes after epoch 1710. This scenario is clearly seen in the snapshots (Figure 1), in global population dynamics (Figure 4) and in global temperature dynamics (sub Figure 2 (b)). The local population dynamics (Figure 3) and local temperature (sub Figure 2 (a)) at a typical habitat (57, 50) shows that the dynamics freezes even quicker (epoch 1055). All trajectories show initial fluctuations but evolve to complete stationarity.





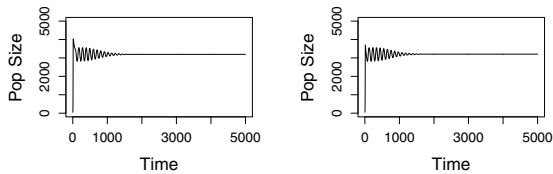
(a) Local Temp. at habitat (57, 50) (b) Global Surface Temp.

Figure 2: Regular CML: Temperature dynamics  $D = 0.2$  and  $NL = 0.001$



(a) Black Daisy Population (b) White Daisy Population

Figure 3: Regular CML: Local population dynamics at habitat (57, 50);  $D = 0.2$  and  $NL = 0.001$



(a) Black Daisy Abundance (b) White Daisy Abundance

Figure 4: Regular CML: Global population dynamics;  $D = 0.2$  and  $NL = 0.001$

## II. Daisyworld with Static Local and Non-local Couplings (Small-World Network)

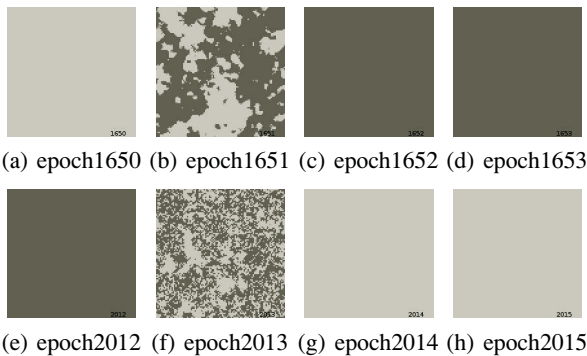
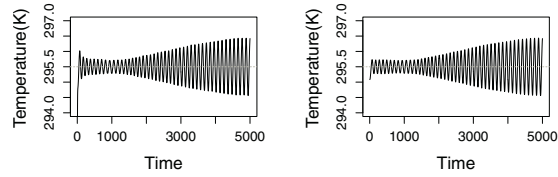
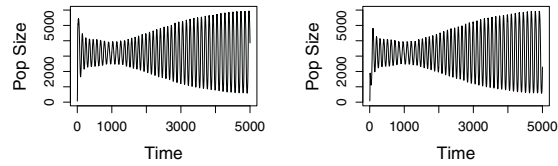


Figure 5: Newman-Watts ( $p = 0.05$ ) :  $D = 0.2$  and  $NL = 0.001$  in 2D  $100 \times 100$  Small-world CML



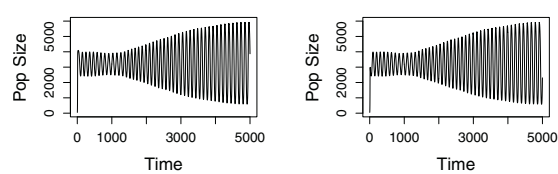
(a) Local Temp. at habitat (52, 58) (b) Global Surface Temp.

Figure 6: Newman-Watts CML ( $p = 0.05$ ): Temperature dynamics  $D = 0.2$  and  $NL = 0.001$



(a) Black Daisy Population (b) White Daisy Population

Figure 7: Newman-Watts CML ( $p = 0.05$ ): Local population dynamics at habitat (52, 58);  $D = 0.2$  and  $NL = 0.001$



(a) Black Daisy Abundance (b) White Daisy Abundance

Figure 8: Newman-Watts CML ( $p = 0.05$ ): Global population dynamics;  $D = 0.2$  and  $NL = 0.001$

Each dynamic unit (habitat) is coupled through a small-world topology initialised through the NW mechanism. The topology remains static but the states of the habitats change dynamically. This ecosystem exhibits a periodic behaviour (Figure 5). The cyclic behaviour is understood by observing the trajectories in temperature dynamics (Figure 6), local population dynamics (Figure 7) and global population dynamics (Figure 8). This shows that a small change in the underlying topology drastically influences the dynamical properties of the ecosystem, and the transition is very abrupt. Within a single time frame, black dominance may change to white dominance, or vice versa (Figure 5).

## III. Daisyworld with Dynamic Local and Non-local Couplings (Adaptive Network)

The local dynamical linking rule (when a node becomes frozen, we allow that habitat to reciprocally connect to a random active habitat) generates topologies with small-world

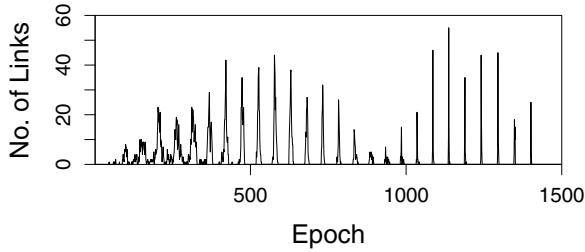


Figure 9: Adapted Reciprocal Links

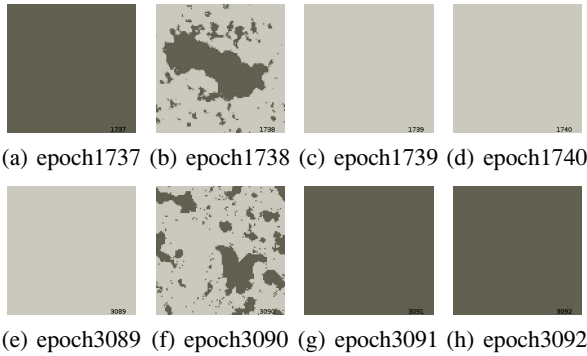


Figure 10: Adaptive CML :  $D = 0.2$  and  $NL = 0.001$  in 2D  $100 \times 100$

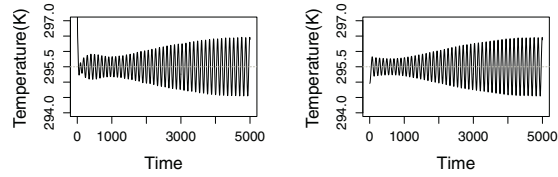
effect (low characteristic path length (CP)) – here we show topologies with high clustering coefficient (CC) (approximately 50% of runs) to compare to NW-CML ( $p = 0.05$ ). It can also generate topologies with low CC. It depends on the random initialization of the temperature of each habitat and random dynamic linking. Typically we observe periodic behaviour (Figure 10) similar to NW-CML. In the corresponding time series plots, the dynamics of both local and global temperature (Figure 11), local population (Figure 12) and global population (Figure 13) exhibit cyclic behaviour. The dynamically adapted reciprocal links are shown in Figure 9.

**Why are NW-CML and adaptive CML similar?**

Table 2: Typical Clustering Coefficients and Characteristic Path Lengths

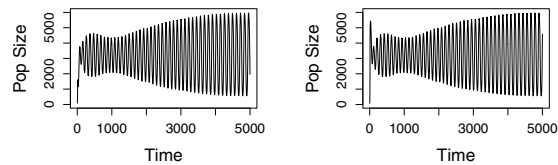
Model	$\bar{C}/C_{\text{regular}}$	$\bar{L}/L_{\text{regular}}$
NW-CML	0.837	0.185
Adaptive CML	0.837	0.189

We saw very similar limit behaviours from NW-CML (Subsection II) and adaptive CML (Subsection III). We can gain understanding through analysing the topological quantifiers (degree distribution, clustering coefficient and characteristic path length) for their network topologies.



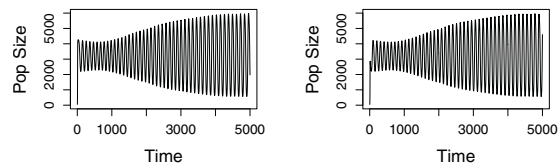
(a) Local Temp. at habitat (56, 57) (b) Global Surface Temp.

Figure 11: Adaptive CML: Temperature dynamics  $D = 0.2$  and  $NL = 0.001$



(a) Black Daisy Population (b) White Daisy Population

Figure 12: Adaptive CML: Local population dynamics at habitat (56, 57);  $D = 0.2$  and  $NL = 0.001$



(a) Black Daisy Abundance (b) White Daisy Abundance

Figure 13: Adaptive CML: Global population dynamics;  $D = 0.2$  and  $NL = 0.001$

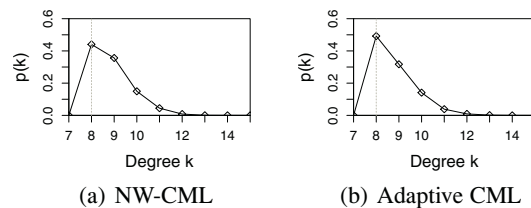


Figure 14: Degree Distribution

The degree distribution of the small-world CML constructed via the NW model in sub section II ranges over  $[8, 14]$  and has an exponential tail reaching zero, as shown in the Figure 14(a). The degree distribution reached by adaptive CML in sub section III, which dynamically linked with reciprocal links, also ranges over  $[8, 14]$  and has an expo-

nential tail reaching zero as shown in the Figure 14(b).

The CC for NW-CML, and that for the final epoch of adaptive CML are almost the same, as are CPs. Figure 14 and Table 2 show the results. The finally-converged adaptive CML is an egalitarian small-world network. This is why we observe a drastic change in the dynamics of the system compared to the regular lattice. It also shows that the topology, constructed statically or dynamically, influences the collective behaviour of the system: relatively small changes in the linkage structure can generate vastly different dynamics.

Table 3: Average( $\pm$ Std.Dev.) Clustering Coefficients and Characteristic Path Lengths

Model	$\bar{C}/C_{\text{regular}}$	$\bar{L}/L_{\text{regular}}$
NW-CML	$0.8412 \pm 0.0024$	$0.1868 \pm 0.001$
Adaptive CML	$0.8928 \pm 0.0639$	$0.2204 \pm 0.0392$

The sections II and III illustrate typical scenarios of NW-CML and adaptive CML. Table 3 shows averages over 25 realisations of adaptive CML model and 25 of NW-CML ( $p = 0.05$ ) model. We ran 100 realizations of adaptive CML and picked 25 that fell in small-world regime (Punithan and McKay, 2013) for comparison purposes – CC in  $[0.98, 0.7]$  and CP in  $[0.3, 0.16]$ . CC and CP are normalised by the values for a regular lattice as proposed in Watts and Strogatz (1998).

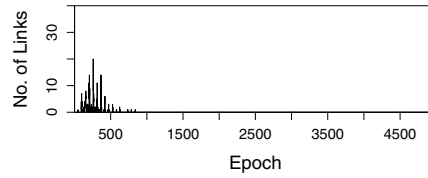
### Topological Evolution

Table 4: Clustering Coefficients and Characteristic Path Lengths

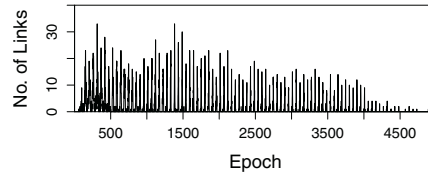
Adaptation	$\bar{C}/C_{\text{regular}}$	$\bar{L}/L_{\text{regular}}$
Quick	0.977	0.295
Slow	0.837	0.238

The evolution of the topology continues until the stationary attractor (frozen local dynamics) of all habitats reach a dynamical attractor – here a limit cycle. Some samples adapt quickly, reaching a stable topology around the 500<sup>th</sup> epoch (Figure 15 (a) – Quick Adaptation), while a few evolve almost until the 5000<sup>th</sup> epoch (Figure 15 (b) – Slow Adaptation). Their degree distribution (Figure 16), clustering coefficient and characteristic path (Table 4) show that both evolve to small-world networks, although at different rates.

The collective dynamics in both quick and slow adaptations (Figures 18 and 19) show the shift in dominance is not so abrupt as in Figures 5 and 10 (see epoch nos.). The emergent property – the temperature cycles – depicted in Figure 17 (in both adaptations) have different limit ranges. In sub Figure 17 (b), the shift in dominance takes more time initially, eventually speeding up owing to the increasing limit height. The abruptness is clear in the corresponding global temperature plots – compare the limits in sub fig-

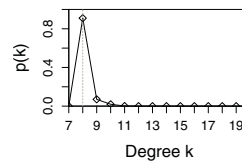


(a) Quick Adaptation

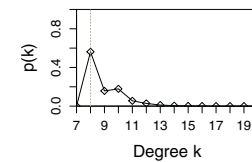


(b) Slow Adaptation

Figure 15: Adapted Reciprocal Links

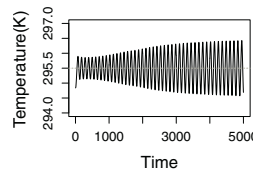


(a) Quick Adaptation

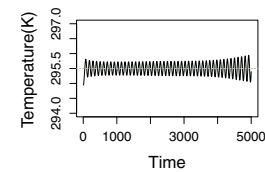


(b) Slow Adaptation

Figure 16: Degree Distribution



(a) Quick Adaptation



(b) Slow Adaptation

Figure 17: Global Temperature dynamics  $D = 0.2$  and  $NL = 0.001$

ures 6 (b), 11 (b), 17 (a) and 17 (b). The degree distribution shows that relatively few reciprocal links are added (sub figure 16 (a)). This confirms even a few long-distance links – if they are the right links – lead to drastic behaviours changes.

### Conclusion

We have analysed the connectivity changes in a complex adaptive ecosystem combining life-environment, state-topology and density-growth feedback loops. The results illustrate the capacity of the adaptive ecosystem to self-organise to a complex ecosystem (small-world network)

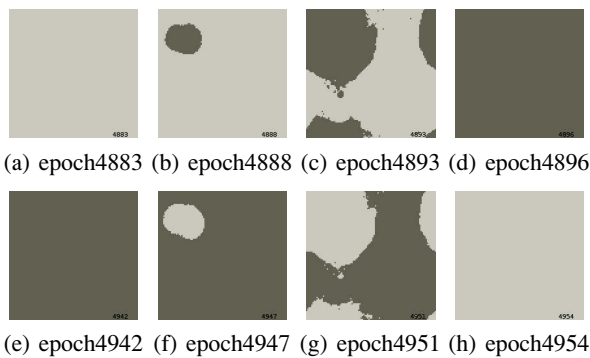


Figure 18: Quick Adaptation :  $D = 0.2$  and  $NL = 0.001$  in 2D  $100 \times 100$

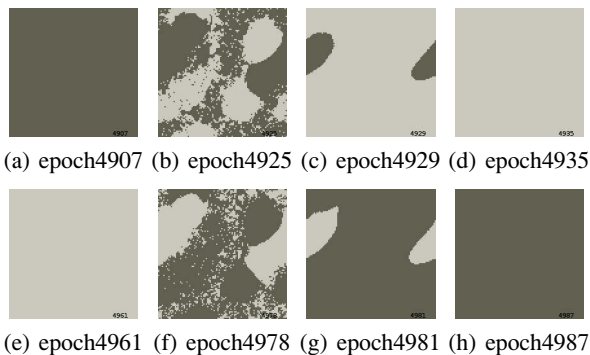


Figure 19: Slow Adaptation :  $D = 0.2$  and  $NL = 0.001$  in 2D  $100 \times 100$

through a simple dynamical rule – frozen habitats (nodes) gain reciprocal non-local neighbours (links). This ecosystem exhibits similar behaviour to contagion systems such as memes or virus – cyclic behaviours – without any external intervention, requiring only the adding of new reciprocal connections under certain locally-defined conditions.

Even a small change in the connectivity, with almost no effect on the mean degree of the ecosystem, leads to a drastic behaviour change from the grid network. It is much more like the real-world behaviour we see in social systems (seasonal rise and fall of fads), economic systems (booms and busts) etc.. This “small cause, large effect” behaviour draws analogies with popular metaphors black swan (low probable but high-impact events) (Taleb, 2010), butterfly effect (sensitive dependence on initial conditions) (Hilborn, 2004) and tipping point (little things make a big difference) (Gladwell, 2006). Though the collective dynamics change in varying ways, we still observe the emergent property – self-regulation of the temperature at around  $295.5K$ .

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