EVOLUTION OF SPATIAL PATTERNS IN HOST-PARASITOID METAPOPULATION

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PLAN

- Discrete Population Growth Dynamics – single and interacting species
- Dynamics of populations under constant migration – single and interacting species
- Metapopulation and types of connectivity
- Metapopulation dynamics under different connectivities
- Summary & implications

POPULATION GROWTH

Population

Collection of units capable of growth

[viruses, cells, insects, birds, fishes, humans]

Models of population growth processes are used to describe experimental data and predict future trends in many areas

- Ecology
- Wild-Life Biology & Conservation
- Demography
- Natural Resources Harvesting
- Epidemiology

What determines the distribution and abundance of a population ?

BIRTH
IMMIGRATION

NET GROWTH

DEATH
EMIGRATION
HARVESTING

SURVIVAL
(dynamics)

EXTINCTION
(size dependence, mode)

Types of Growth

- **Continuous growth** where generations overlap

  (Differential equations)

- **Discrete growth** where

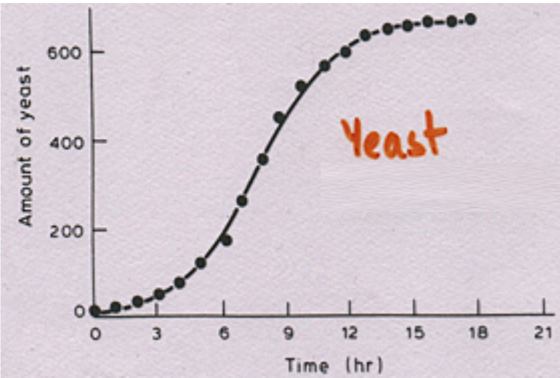
  (a) generations do not overlap

  (b) there is age and stage structure of birth

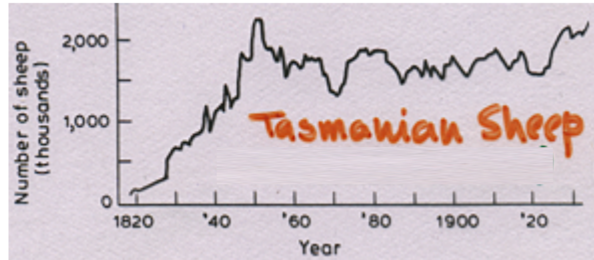
  (Discrete equations)

Time series of different populations

How do natural populations behave ?

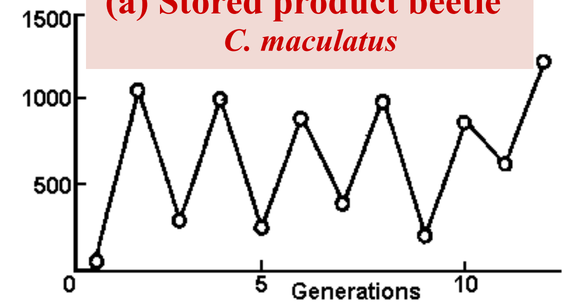


(Pearl, 1927)

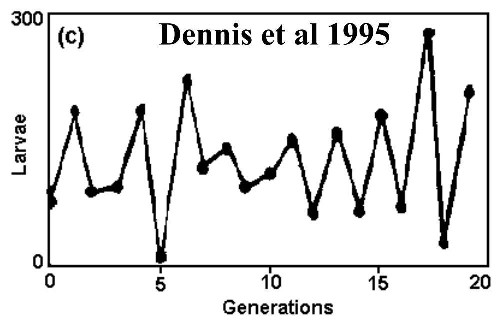


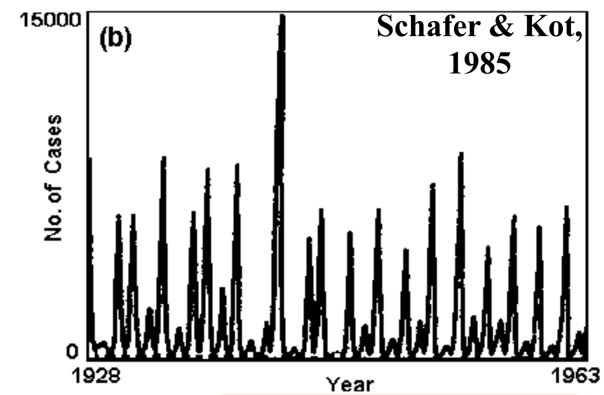
(Davidson, 1938)

(a) Stored product beetle
C. maculatus

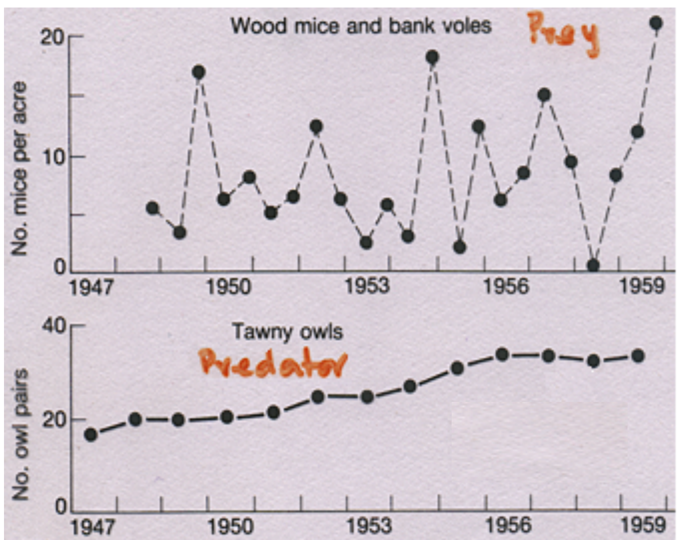


(c) Flour beetle (*T. casteneum*)



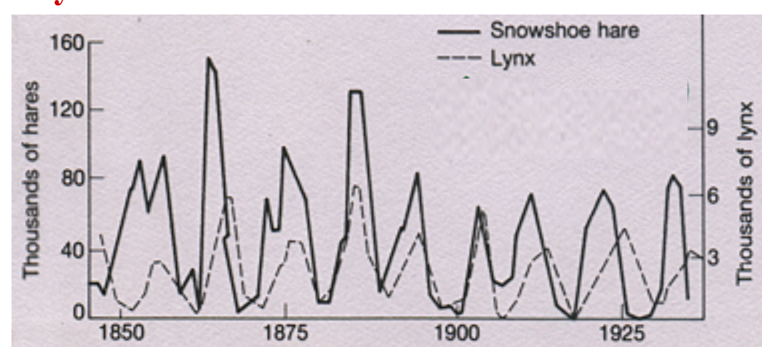


(b) Cases of measles



(b) Prey-Predator system
(Southern, 1970)

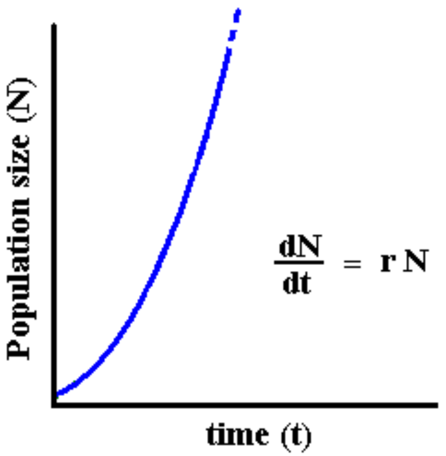
(b) Prey-Predator system
(Maclulick, 1937)



Continuous breeding with overlapping generations

***Simplest differential equation model for single population is the* Logistic Growth Model**

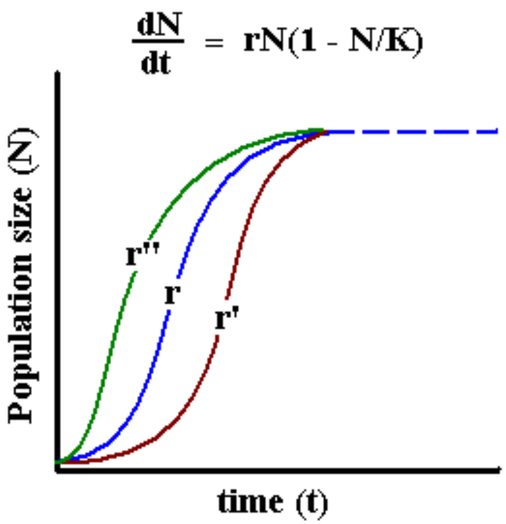
In unlimited environmental resources



r = growth rate

K = carrying capacity of environment

In limited-resources



In logistic growth model a single population can only grow, stabilise or die depending on r and K.

Environmental noise

Time lag

Growth rate regulation

can induce other types of dynamics

Discrete Population Growth Dynamics

single species

and

interacting species

Discrete growth with non-overlapping generations

A simple model for discrete growth $N_{t+1} = f(N_t)$

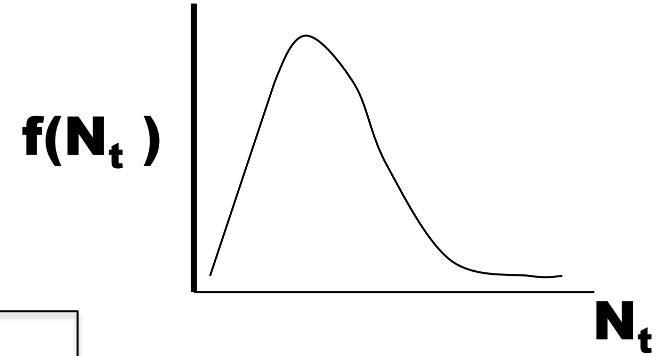
"Hump" like shape with a unique maximum

Discrete Logistic Equation

$$N_{t+1} = [1 + r'(1 - N_t / K)]\, N_t$$

$X = [r/(r+1)]\,(N/K)$

$r' = (1+r)$



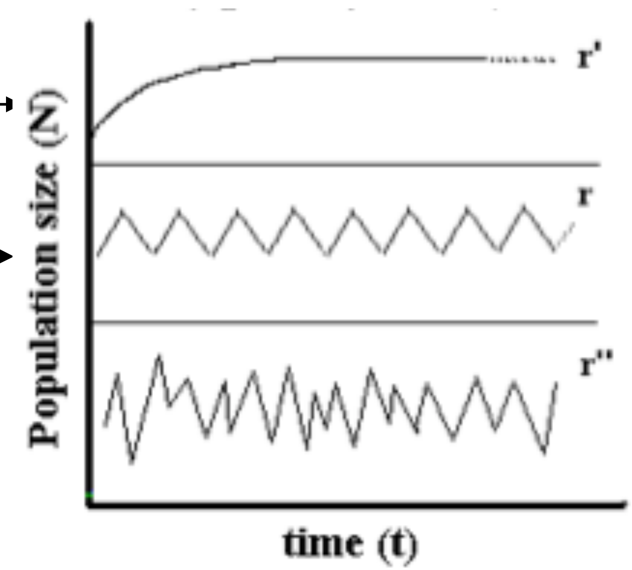
$$\boxed{X_{t+1} = r'\, X_t(1 - X_t)}$$

A single population in this model shows a variety of dynamics with different values of r

STABLE

OSCILLATORY

CHAOTIC



Simple models for discrete single populations

Logistic map $X(t+1) = r\,X(t)[\,1 - X(t)]$

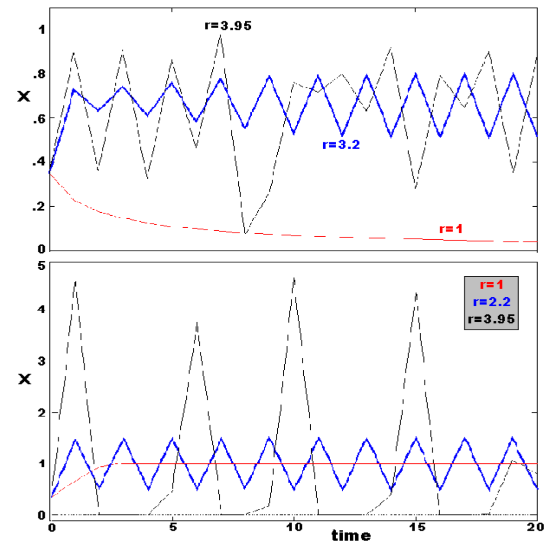
Exponential map $X(t+1) = X(t)\exp\{r\,[1 - X(t)]\}$

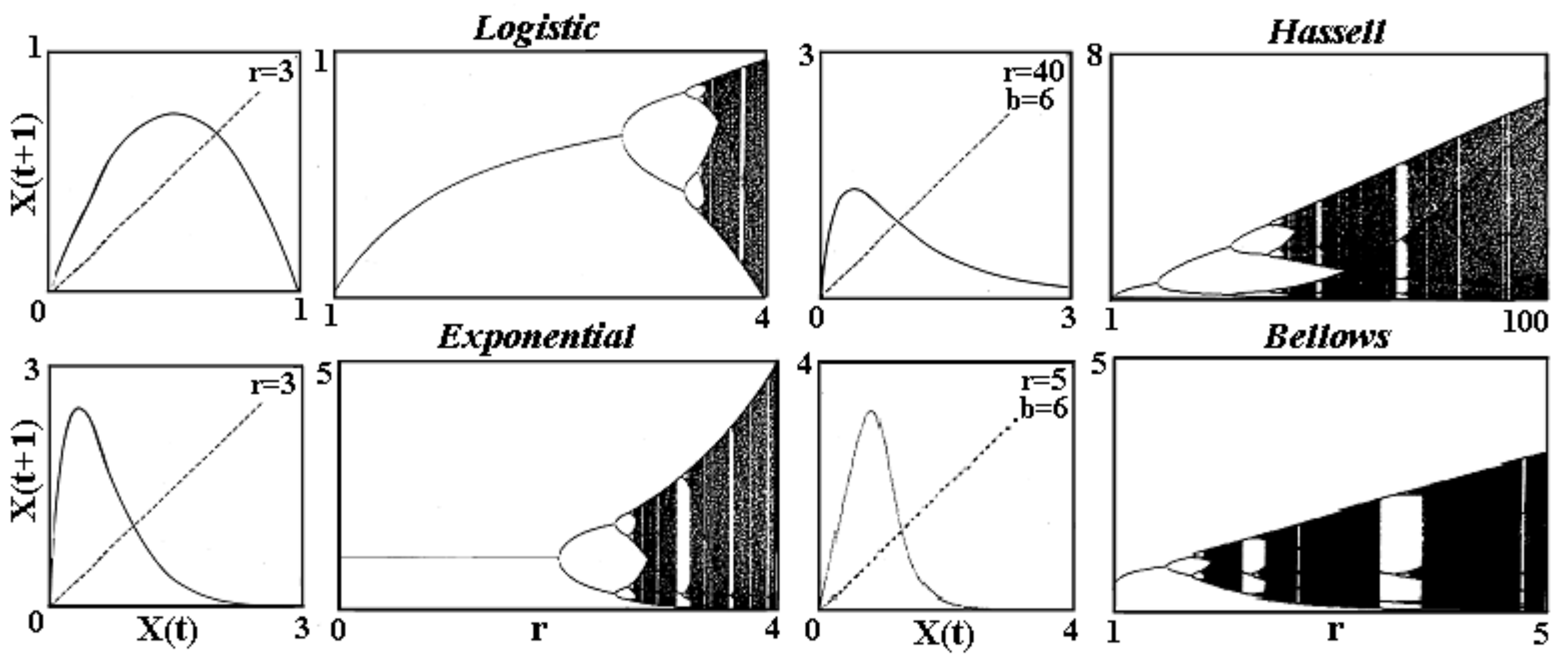
Hassell map $X(t+1) = r\,X(t) / (1 - X(t))^b$

Bellows map $X(t+1) = r\,X(t) / (1 - X(t)^b)$

r - *intrinsic growth rate*

X - *population size (scaled by carrying capacity).*





Skellam, Biometrika, 1951; Ricker, J.Fish.Res.Bd.Can., 1954; May, Nature, 1976; Hassell, J.Anim.,Ecol., 1976; Bellows, J.Anim.Ecol., 1981.

All unidimensional "single-hump" discrete models show similar sequence of dynamics - stable to oscillatory to chaos through period doubling bifurcations - with increasing growth rate.

A general class of models exhibiting "universal" dynamics.

(Feigenbaum 1978 J. Stat. Phys., May 1976 Nature, Oster & May 1976 Am.Nat.)

Used interchangeably in Ecology to describe population growth.

Problems

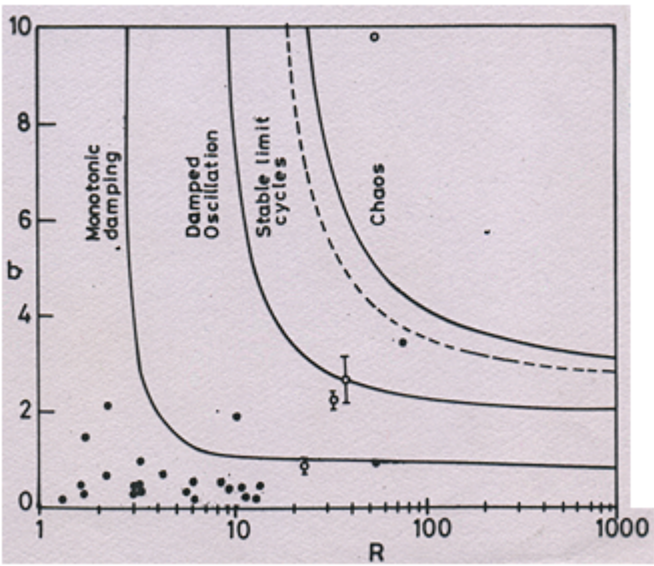
Seemingly stochastic behaviour observed in data can be explained by complex, chaotic dynamics arising from nonlinearities in these simple deterministic models.

Chaos is associated with high risk of extinction and hence should be evolutionary selected against.

How do natural populations behave ?

A large scale study Hassell (1974, 1976) J. Anim. Ecol.

24 field and 4 laboratory populations of insects studied



● *field populations* **Stable**

○ laboratory populations **Unstable**

Hassell map

$$X(t+1) = r\, X(t) / (1 - X(t))^{b}$$

boundaries in the (R-b) plane are obtained theoretically for different dynamics

Questions: Is the erratic variation in population size due to noise ? Or, chaos ?

Why do these populations show stable dynamics in nature ?

Do ecological processes play any role in stabilising dynamics ?

Interacting Species Population: Host - Parasitoid system

$$H_{t+1} = f(H_t,P_t) = rH_t(1-H_t)\exp[-\beta P_t]$$

$$P_{t+1} = g(H_t,P_t) = cH_t(1-\exp[-\beta P_t])$$

H_t, P_t - *host & parasite population size at generation t*

r - *intrinsic reproductive rate of host in absence of parasite*

c - *average number of viable eggs laid by a parasite on a host*

β - *searching efficiency of parasite to attack the host*

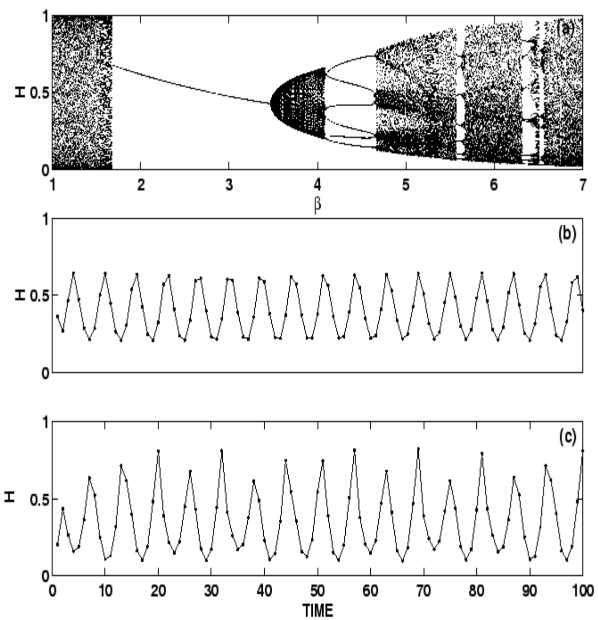
exp[-βP_t] - *fraction of host population escaping parasitism*

Parasite grows only in presence of the host

r = 4

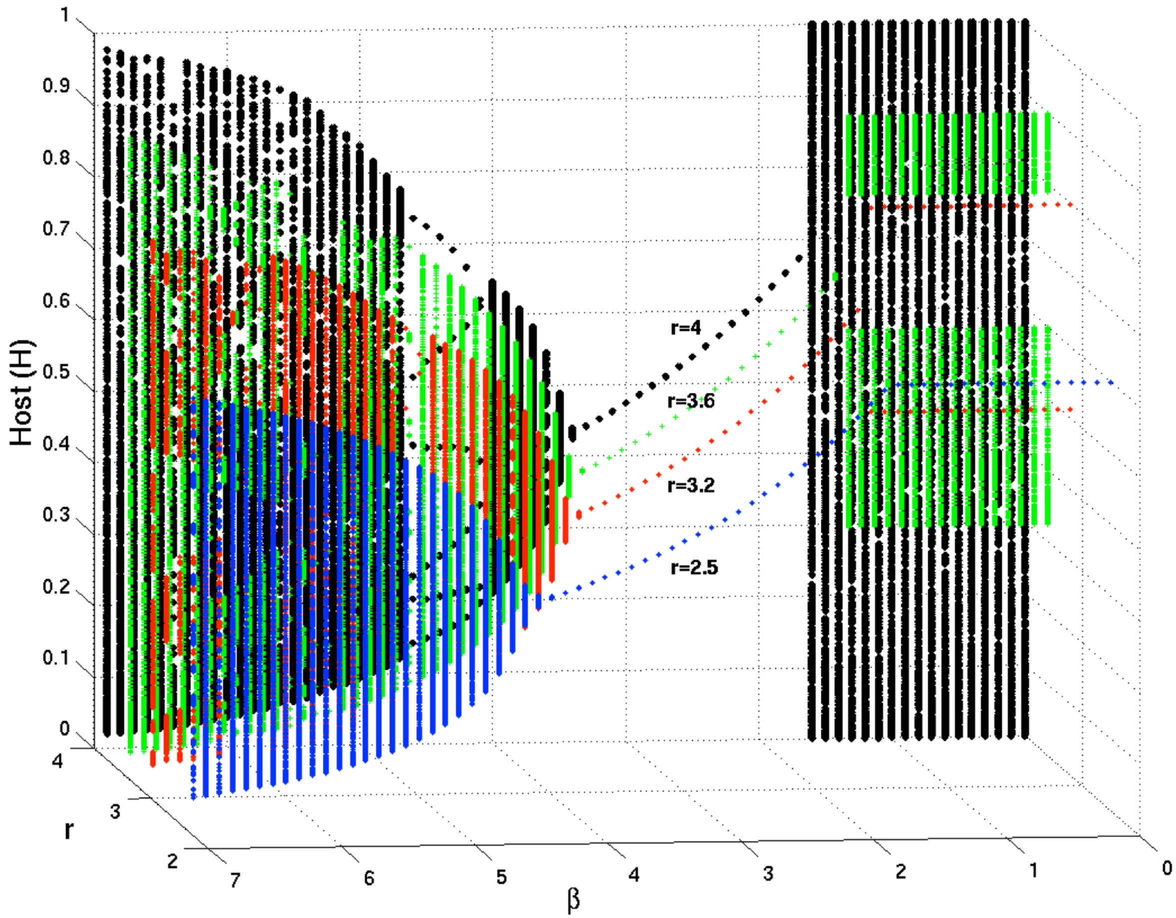
β = 4 quasi-periodic

β = 5 chaotic



In absence of the parasite, the host has Logistic growth, and exhibits a variety of dynamics, from equilibrium to chaos through period-doubling bifurcations with increasing μ, in its population dynamics.

The bifurcation diagram of H with β for four different values of r.



Thus ecological interactions (e.g., trophic relationship between species) can modulate population dynamics and lend stability

Dynamics of populations under constant migration

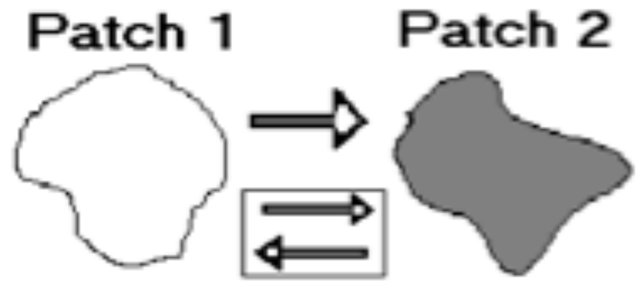
single species

and

interacting species

Population

Interacting
(multiple patches with migration corridors)



Single
(isolated patch)

Immigration Increases size
Emigration Reduces size, Extinction

Most populations in nature are isolated subpopulations connected through migration

Similar ecological processes are *dispersal, harvesting, recruitment, culling, release, refuge, immunize/quarantine, etc.*

Single discrete population models under constant migration (L)

Logistic map $X(t+1) = r\,X(t)[\,1 - X(t)]$

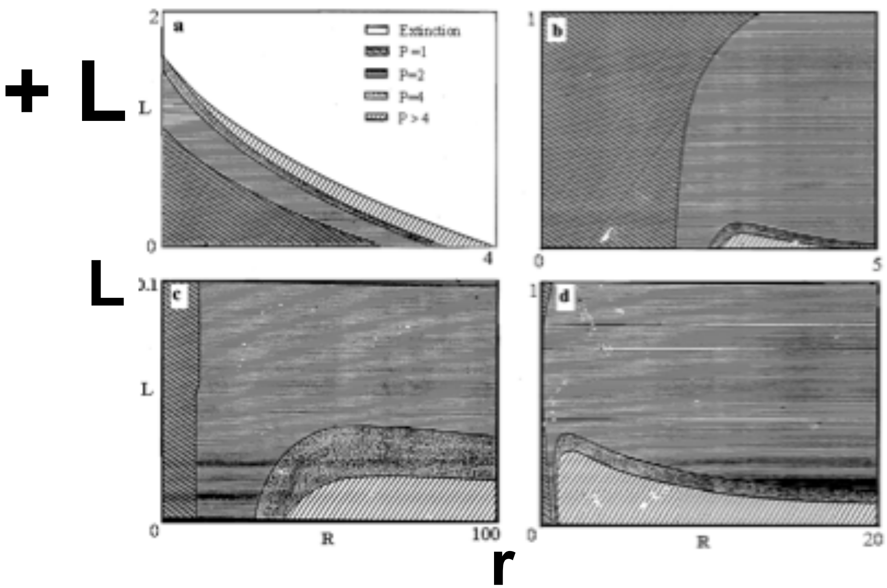
Exponential map $X(t+1) = X(t)\exp\{r\,[1 - X(t)]\}$

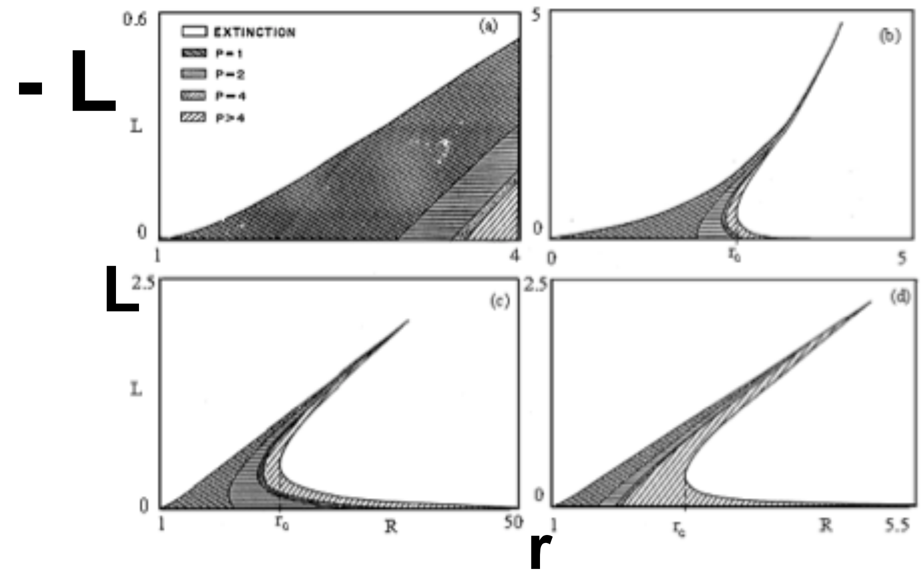
Hassell map $X(t+1) = r\,X(t) \,/\, (1 - X(t))^{b}$

Bellows map $X(t+1) = r\,X(t) \,/\, (1 - X(t)^{b})$.

Discrete population models under constant migration (L)

(a) Logistic map	$X(t+1) = r\,X(t)[\,1 - X(t)]$	$\pm$ L
(b) Exponential map	$X(t+1) = X(t)\exp\{r\,[1 - X(t)]\}$	
(c) Hassell map	$X(t+1) = r\,X(t)\,/\,(1 - X(t))^b$	
(d) Bellows map	$X(t+1) = r\,X(t)\,/\,(1 - X(t)^b)$.	





(1) Similar models (same universality class) respond differently to ecological processes.

(3) Maps with "tail" (inflexion point) exhibit the *survival-extinction-survival* behaviour

Nonlinearity of density-dependence is important.

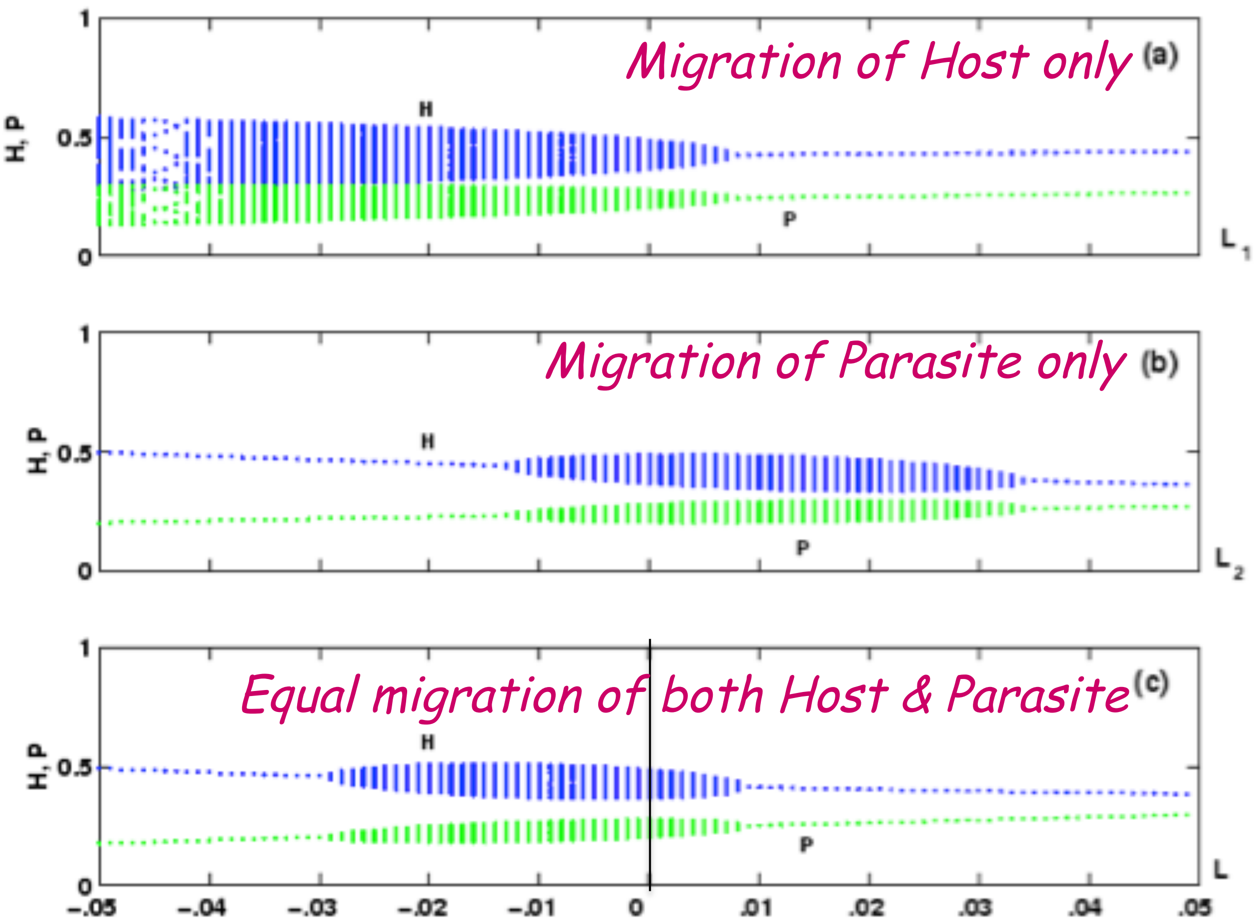
Sinha et al, Phys Rev Lett, Phys Rev E, PNAS (USA), etc

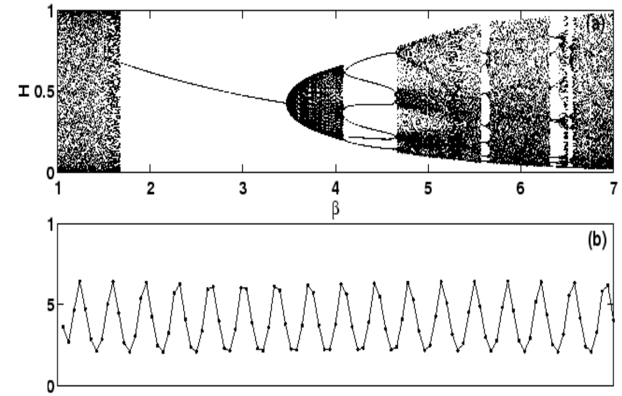
Constant Migration in Host - Parasitoid system

$L=0, \quad r = 4$

$$H_{t+1} = rH_t(1-H_t)\exp[-\beta P_t] + L_1$$

$$P_{t+1} = cH_t(1-\exp[-\beta P_t]) + L_2$$





β = 3.5 quasi-periodic

Population dynamics of Host and Parasitoid show opposite effects for migrations of each species.

Ecological interactions regulate dynamic response.

Sinha et al Phys Rev E, PhysA, etc.

Metapopulation and types of connectivity

Host-Parasitoid metapopulation dynamics under different connectivities

Metapopulation

Subpopulations interacting through migration/dispersal

Migration depends on Spatial Connectivity

(Random; Regular - "n" nearest neighbour, "Small-World", Long distance; All-to-all)

A Model Metapopulation in one dimension

(Coupled map lattice (CML) model)

$$x_{n+1}(i) = (1 - \varepsilon)f(x_n(i) + (\varepsilon/2)[f(x_n(i-1)+f(x_n(i+1))]$$

n = 1,2,….,N ***discrete time steps,***

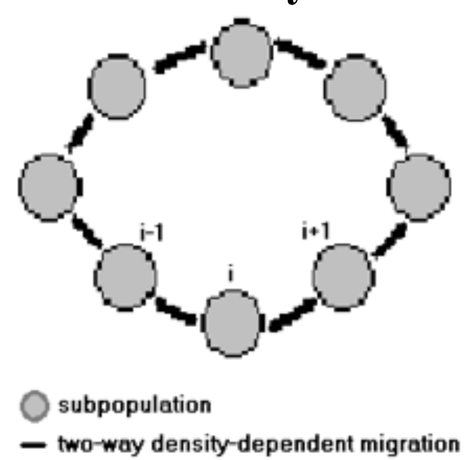
I = 1,2,….,L ***discrete lattice sites***

ε = ***diffusion/coupling to nearest patches,***

f(x) = ***local population growth function*** **or the dynamical system**

= rx(1-x)) for Logistic map

(periodic boundary conditions)



SPATIOTEMPORAL DYNAMICS OF HOST-PARASITE TWO DIMENSIONAL LATTICE METAPOPULATION WITH DISPERSAL TO FOUR NEAREST-NEIGHBOURS

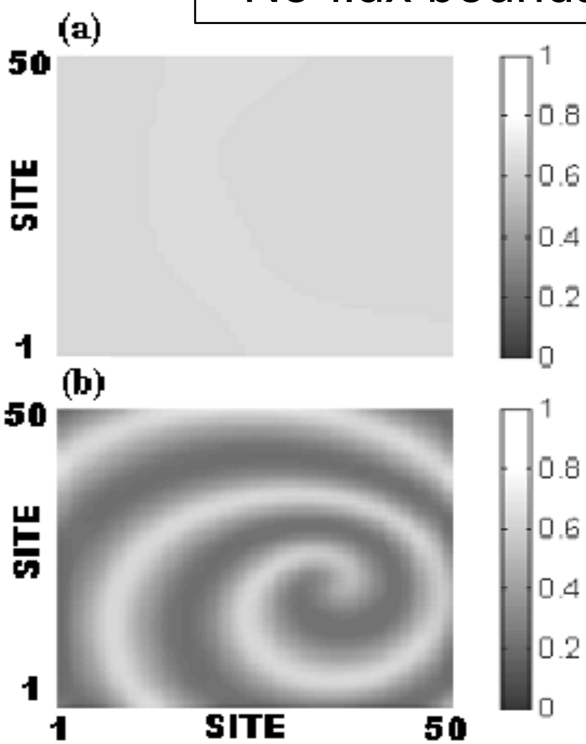
$$H_t'(j,k) = (1- d1)H_t(j,k)+ d1/(nn)\{H_t(j-1,k)+H_t(j+1,k)+H_t(j,k-1)+H_t(j,k+1)\},$$

$$P_t'(j,k) = (1- d2)P_t(j,k) + d2/(nn)\{P_t (j-1,k)+P_t(j+1,k)+ P_t(j,k-1)+P_t(j,k+1)\}$$

$$H_{t+1}(j,k) = rH_t'(j,k)[1-H_t'(j,k)]exp[-bP_t'(j,k)],$$
$$P_{t+1}(j,k) = cH_t'(j,k)\{1-exp[-bP_t'(j,k)]\}$$

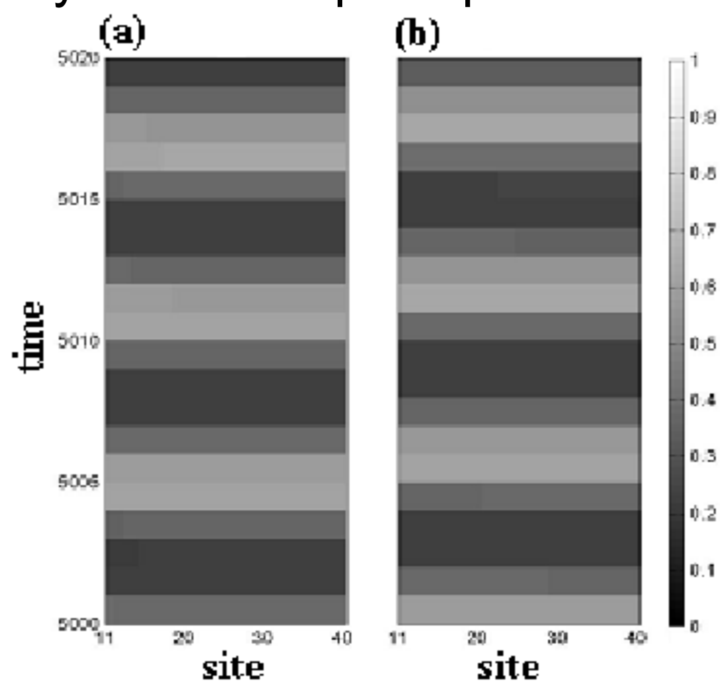
H_t' & P_t' are post-dispersal and H_t & P_t pre-dispersal host and parasite densities in generation t.

No-flux boundary



In 93% cases the lattice shows synchronised spatiotemporal behaviour, few developed spiral patterns

For r = 4, β = 3.5, subpopulation dynamics is quasi-periodic



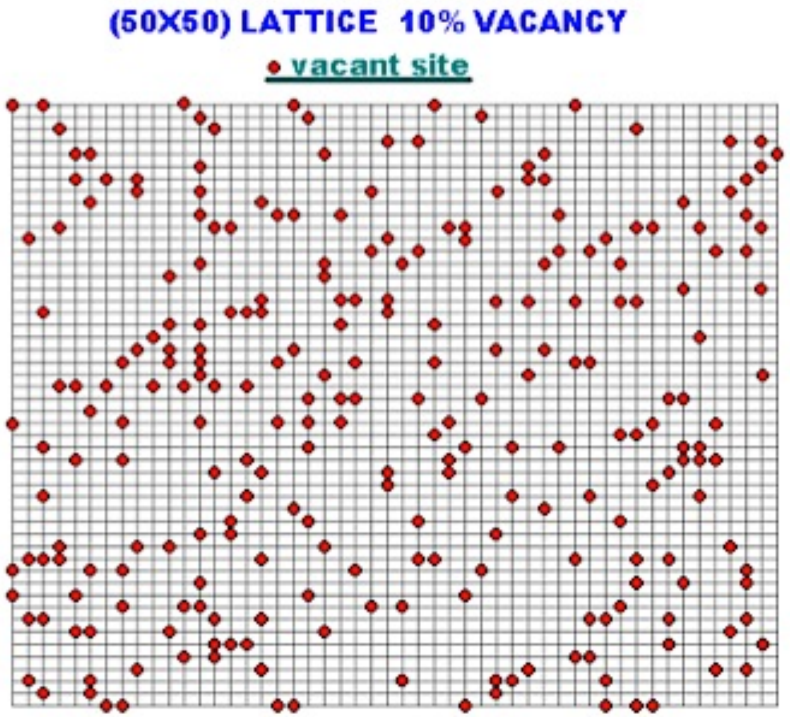
The role of heterogeneity on the spatiotemporal dynamics of host-parasite metapopulation

Two types of heterogeneity

1) Landscape Heterogeneity: Randomly distributed defective sites where no population can grow or disperse. *Landscape fragmentation*

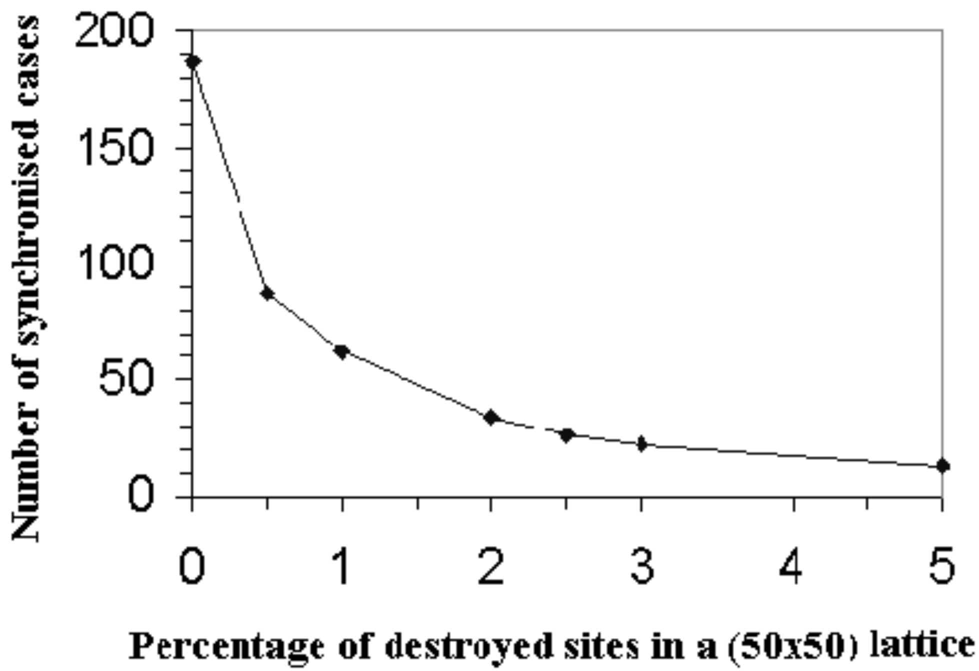
Creates difference in number of neighbours among sites.

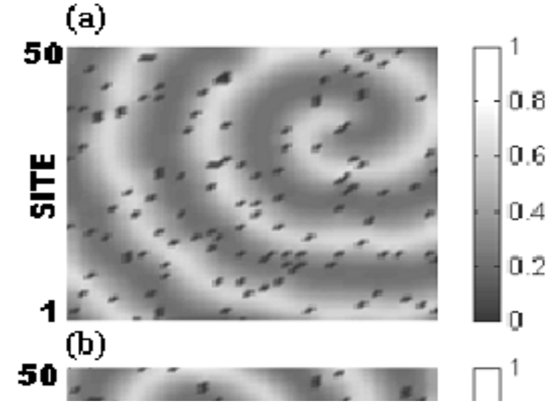
2) Demographic heterogeneity: Randomly distributed sites where the infectivity of parasitoids, β, were different

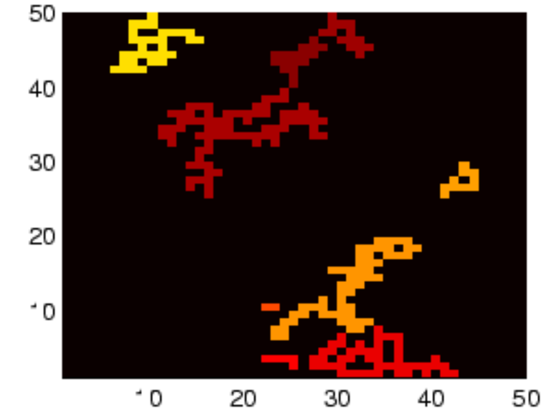


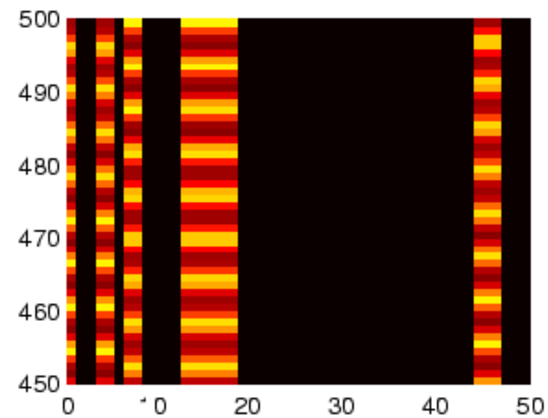
Landscape fragmentation and heterogeneity in parasite attack rates induce asynchrony in spatiotemporal dynamics.

Increasing vacancy increases asynchrony in larger number of lattices.









[Sinha et al,, Ecol.Model.]

Patterned heterogeneities

The dispersal functions to the nearest 8 neighbours in a square lattice is

$$H' = (1 - d_1)H_t(s) + \frac{d_1}{8}\sum_{j=1}^{8} H_t(j)$$

$$P' = (1 - d_2)P_t(s) + d_2\sum_{j=1}^{8} P_t(j)\delta_t^j(s).$$

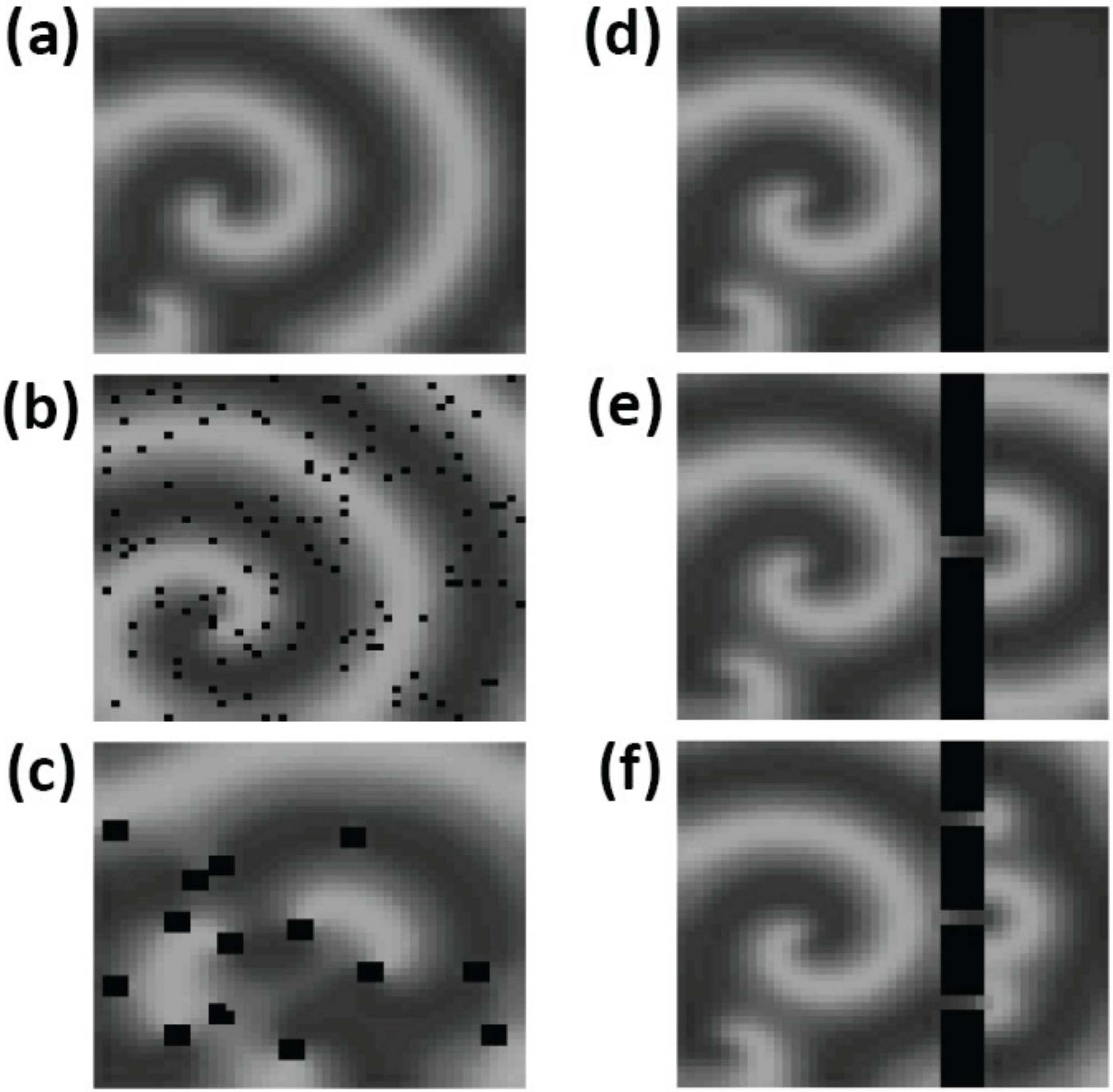
d1 and d2 are the host and parasitoid dispersal coefficients, respectively. The parasitoid dispersal is assumed to be dependent on both the host and the parasitoid densities of the neighbouring patches. The term δ_t^j denotes the proportion of dispersing parasitoid populations from the neighbouring sites (j's) to site s. The functional form is given by:

$$\delta_t^j(s) = C_N\left(\frac{H_t^j(s)}{\sum_{i=1}^{8} H_t^j(i)}\right)^{\eta},$$

where η is known as the 'aggregation index', and CN is a normalising constant such that,

$$\sum_{i=1}^{8} \delta_t^j(i) = 1.$$

Spatial patterns in host metapopulation



Landscape fragmentation

(a) Homogeneous lattice

(b) vacant patches distributed randomly

(c) Clusters of (3 × 3) vacant patches distributed randomly.

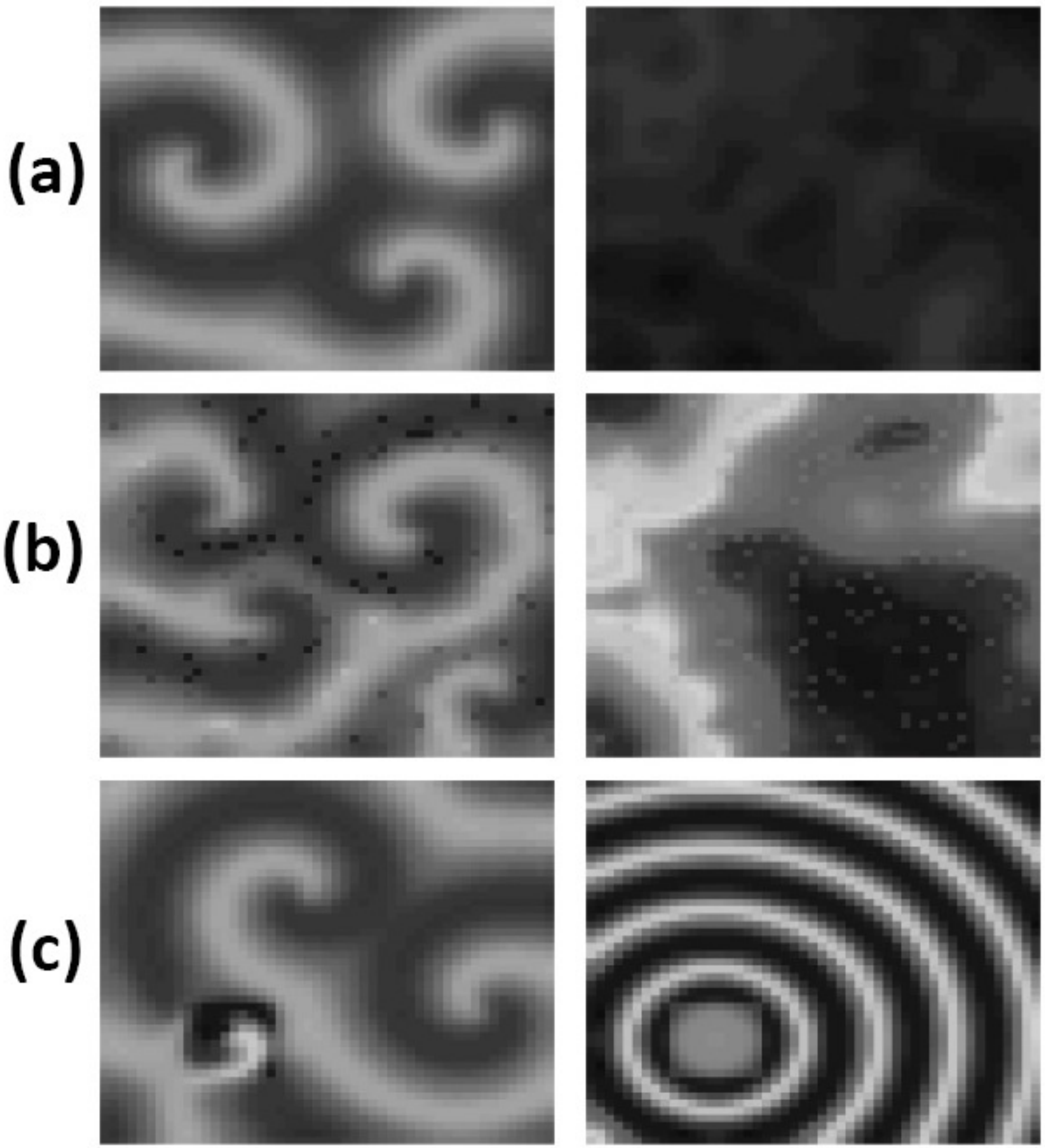
(d) an impermeable barrier of vacant sites dividing metapopulation into two parts;

(e) with one passage,

(f) with three passages.

Spatial patterns in host metapopulation

β = 4 – quasi-periodic, and β = 5, Chaotic dynamics.



(a) Demographically **homogeneous** landscape with Left: β = 4, and Right: β = 5.

(b) Lattices with **demographic heterogeneity** – Left: 5% randomly selected sites have the parasitoid with β = 5, while the rest have β = 4. Right: The opposite of Left, i.e., 5% sites have the parasitoid with β = 4, while the rest have β = 5.

(c) Left: 4% of the total sites form a single sub-lattice of (10 × 10) sites, where the parasitoid populations have β = 5, while the rest of the sites have β = 4.

Right: The opposite of Left, i.e., the single sub-lattice have parasitoid populations with β = 4, while the other sites have β = 5.

SUMMARY

- ✧ Diverse patterns of species persistence, abundance and distribution are seen in nature. Ecological interactions, environmental and habitat heterogeneity, demographic and genetic inhomogeneity - are some of the factors that shape population persistence, spatial distribution, and diversity of the species.

- ✧ We have done systematic study of discrete generation single species and interacting Host-Parasitoid population dynamics in single isolated subpopulations and in metapopulations, where migration occurs between the subpopulations. We have shown how ecological interactions and spatial connectivities can modulate population dynamics. Both have significant role in altering dynamics of population growth.

- ✧ We model the effect of various forms of environmental (landscape and demographic) heterogeneities on the spatial dynamics of host-parasitoid metapopulations. These different forms of heterogeneity, coupled to different connectivity patterns of the habitat patches, lead to evolution of different spatial patterns in population distributions.

- ✧ The results explore the roles of different types of dispersal barriers and coexistence of different genotypes of host and parasitoid populations in migration and disease spread. They may also aid in biodiversity policy-making by helping in the design of conservation corridors.