Vegetation Patterns in Semi-Arid Environments

Jonathan A. Sherratt

Department of Mathematics
and Maxwell Institute for Mathematical Sciences
Heriot-Watt University

Mathematical and Theoretical Ecology 2011
19-21 September 2011

This talk can be downloaded from my web site
`www.ma.hw.ac.uk/~jas`

Outline

Vegetation Pattern Formation

Bushy vegetation in Niger

Mitchell grass in Australia

(Western New South Wales)

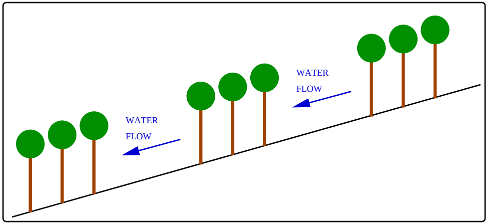
- Banded vegetation patterns are found on gentle slopes in semi-arid areas of Africa, Australia and Mexico
- First identified by aerial photos in 1950s
- Plants vary from grasses to shrubs and trees

Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water

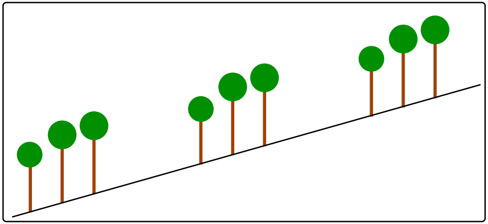
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



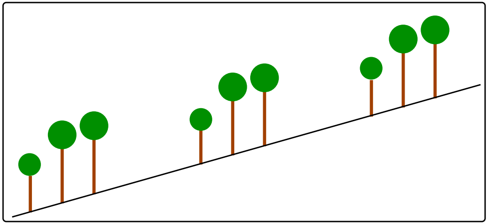
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



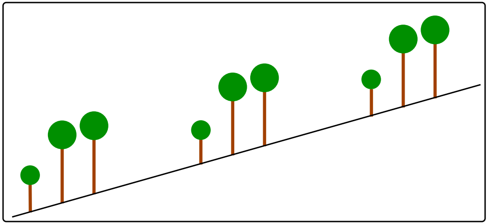
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



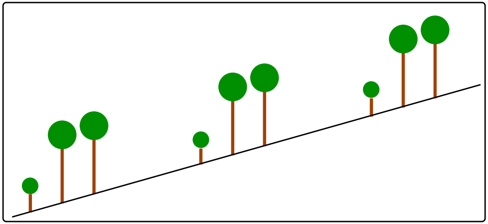
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



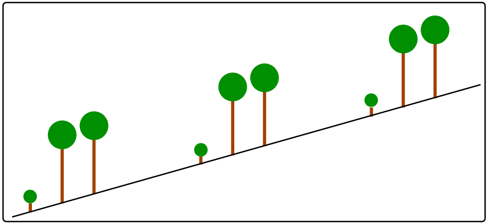
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



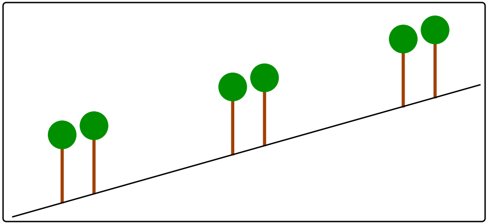
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



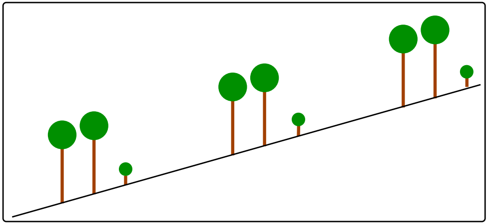
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



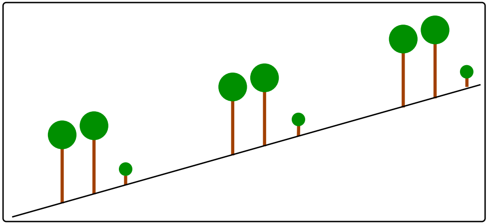
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



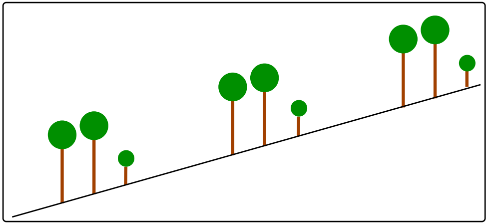
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



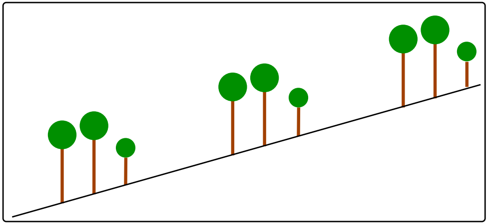
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



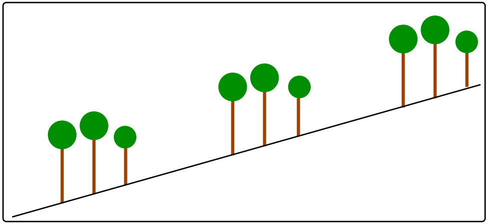
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



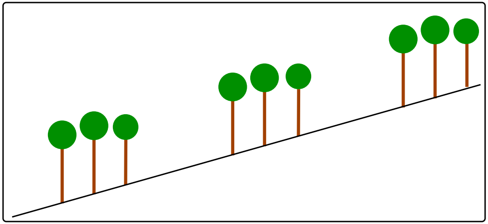
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



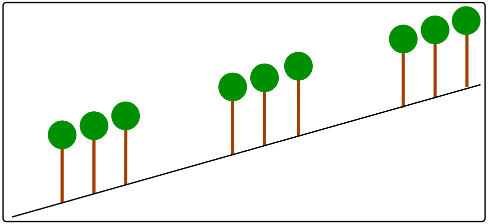
Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



Mechanisms for Vegetation Patterning

- Basic mechanism: competition for water
- Possible detailed mechanism: water flow downhill causes stripes



- The stripes move uphill (very slowly)

Two Key Ecological Questions

- How does the spacing of the vegetation bands depend on rainfall, herbivory and slope?
- At what rainfall level is there a transition to desert?

Outline

1. Ecological Background
2. The Mathematical Model
3. Linear Analysis
4. Travelling Wave Equations
5. Conclusions

Mathematical Model of Klausmeier

Rate of change of water	=	Rainfall – Evaporation	–	Uptake by plants	+	Flow downhill
Rate of change plant biomass	=	Growth, proportional to water uptake	–	Mortality	+	Random dispersal

$$\partial w/\partial t = A - w - wu^2 + \nu\partial w/\partial x$$

$$\partial u/\partial t = wu^2 - Bu + \partial^2 u/\partial x^2$$

Mathematical Model of Klausmeier

Rate of change of water	=	Rainfall – Evaporation	–	Uptake by plants	+	Flow downhill
Rate of change plant biomass	=	Growth, proportional to water uptake	–	Mortality	+	Random dispersal

$$\partial w/\partial t = A - w - wu^2 + \nu \partial w/\partial x$$

$$\partial u/\partial t = wu^2 - Bu + \partial^2 u/\partial x^2$$

The nonlinearity in wu^2 arises because the presence of roots increases water infiltration into the soil.

Mathematical Model of Klausmeier

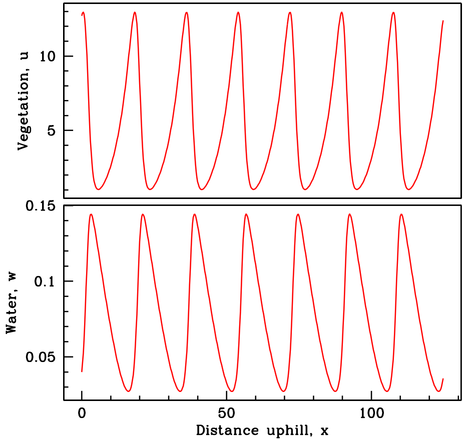
Rate of change of water	=	Rainfall – Evaporation	–	Uptake by plants	+	Flow downhill
Rate of change plant biomass	=	Growth, proportional to water uptake	–	Mortality	+	Random dispersal

$$\partial w/\partial t = A - w - wu^2 + \nu \partial w/\partial x$$

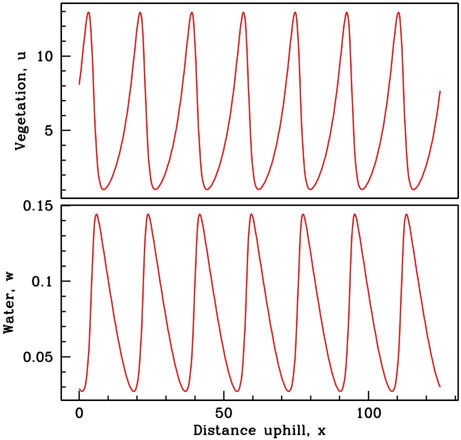
$$\partial u/\partial t = wu^2 - Bu + \partial^2 u/\partial x^2$$

Parameters: A: rainfall B: plant loss ν: slope

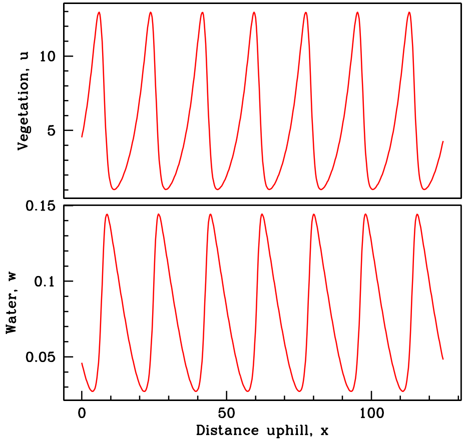
Typical Solution of the Model



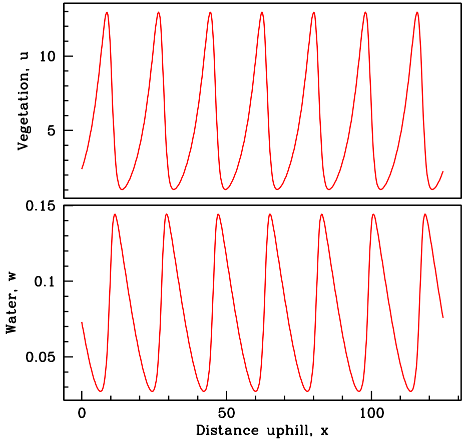
Typical Solution of the Model



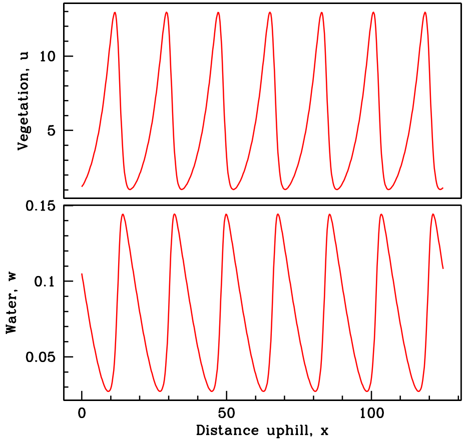
Typical Solution of the Model



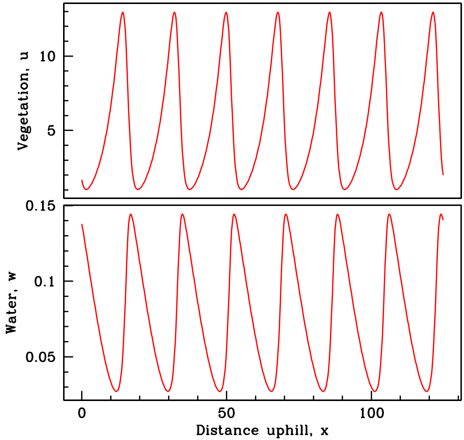
Typical Solution of the Model



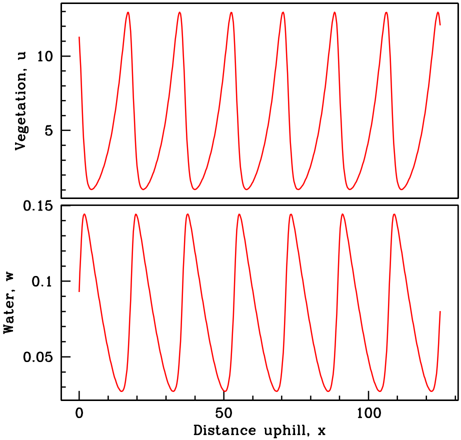
Typical Solution of the Model



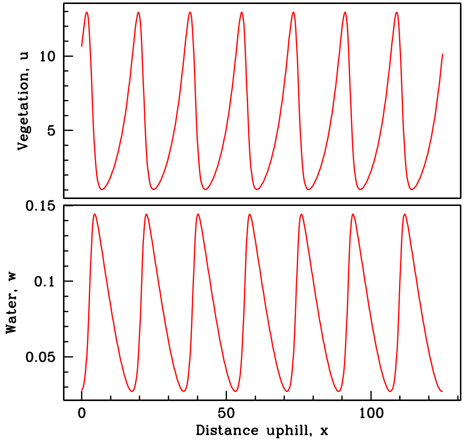
Typical Solution of the Model



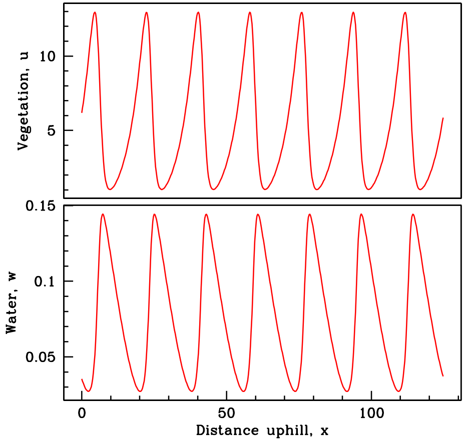
Typical Solution of the Model



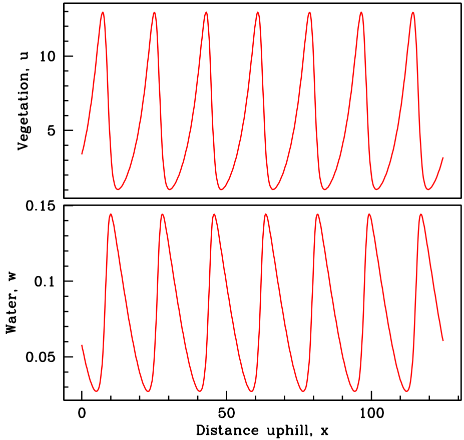
Typical Solution of the Model



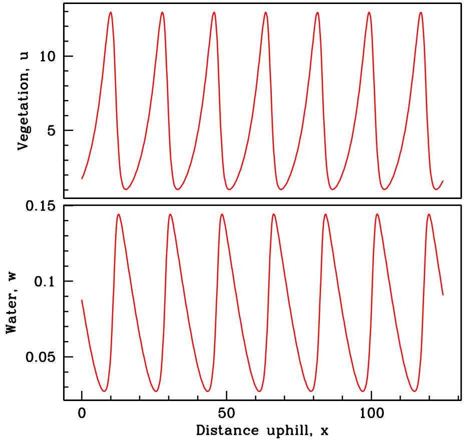
Typical Solution of the Model



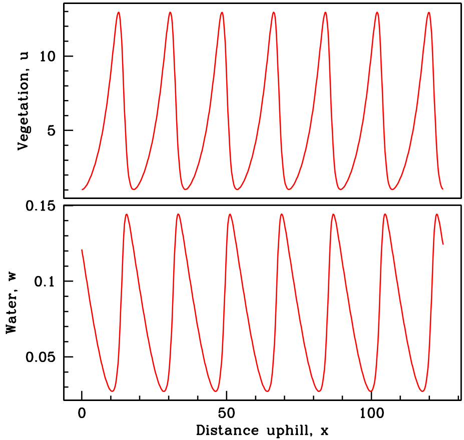
Typical Solution of the Model



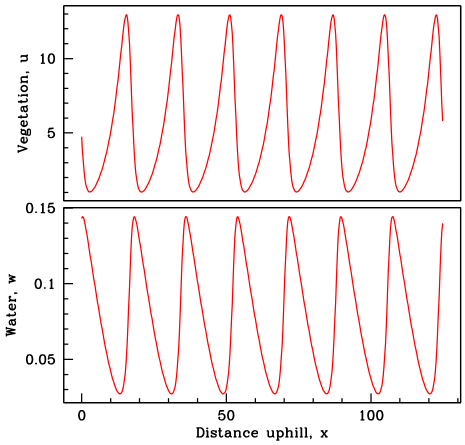
Typical Solution of the Model



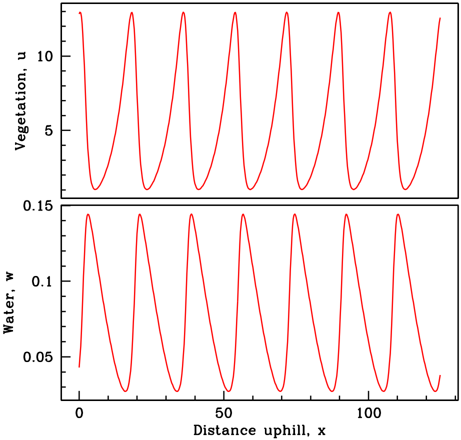
Typical Solution of the Model



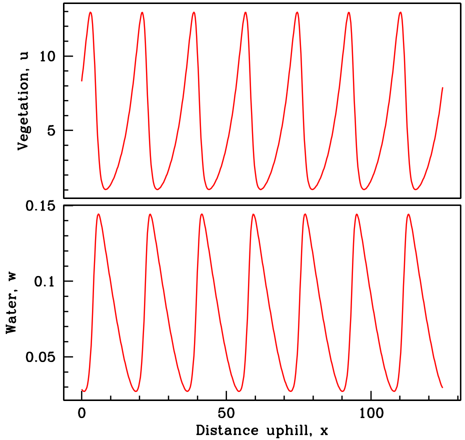
Typical Solution of the Model



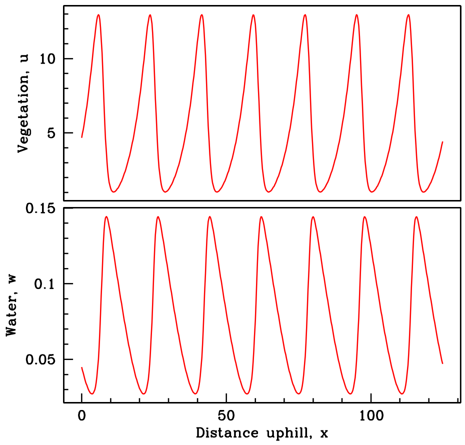
Typical Solution of the Model



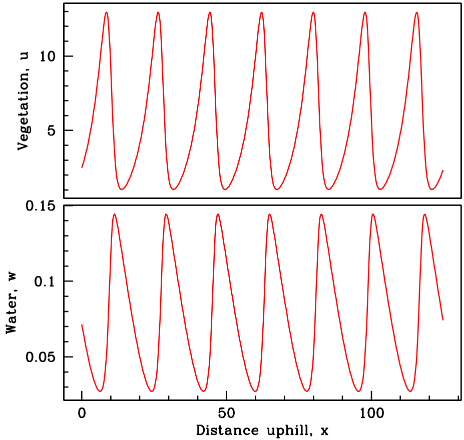
Typical Solution of the Model



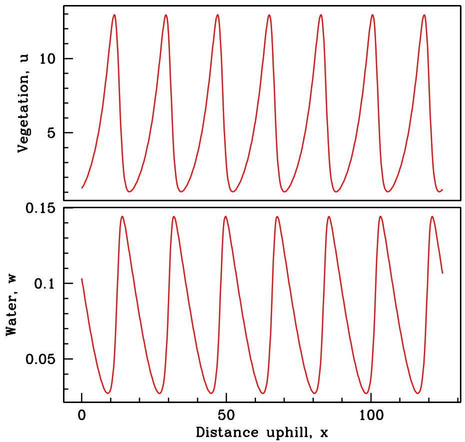
Typical Solution of the Model



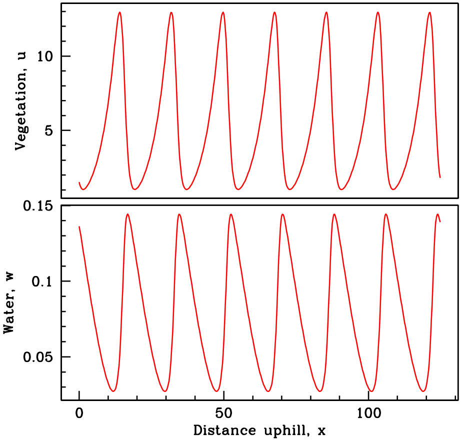
Typical Solution of the Model



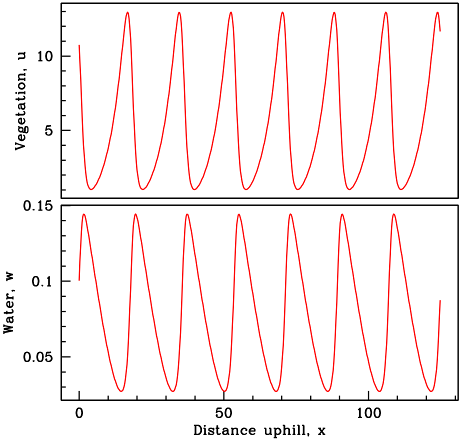
Typical Solution of the Model



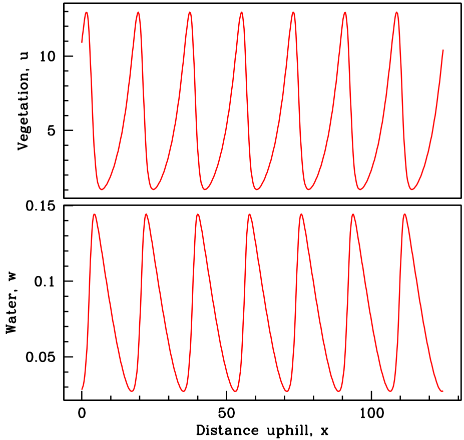
Typical Solution of the Model



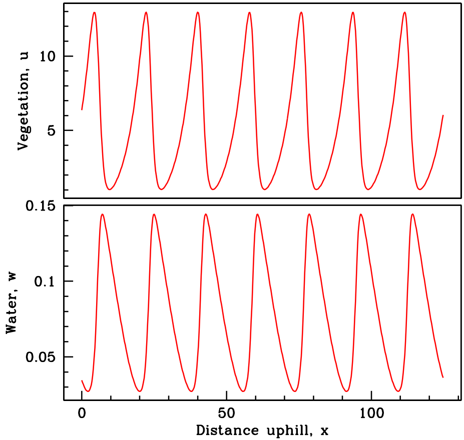
Typical Solution of the Model



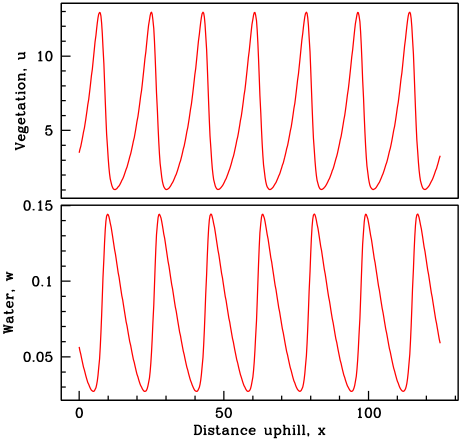
Typical Solution of the Model



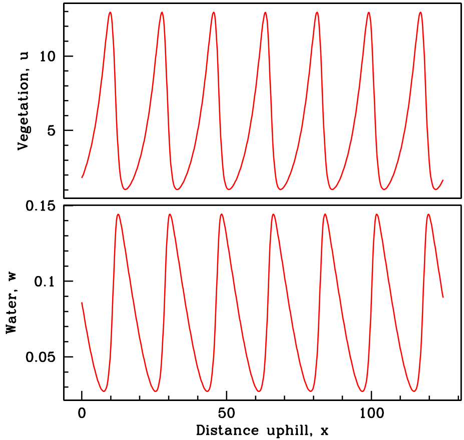
Typical Solution of the Model



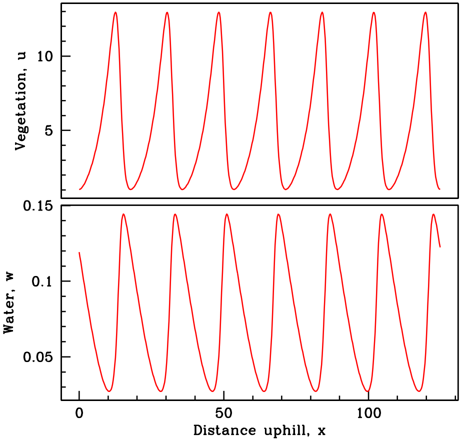
Typical Solution of the Model



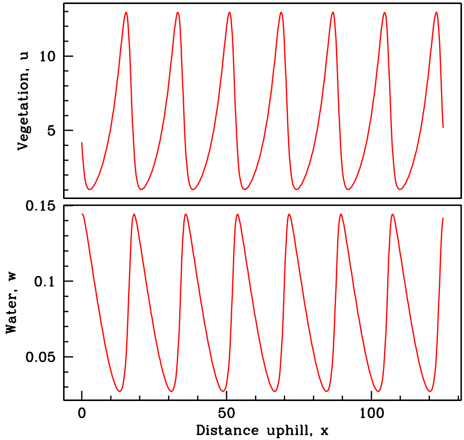
Typical Solution of the Model



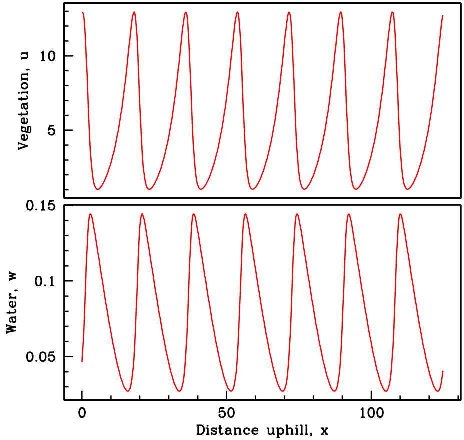
Typical Solution of the Model



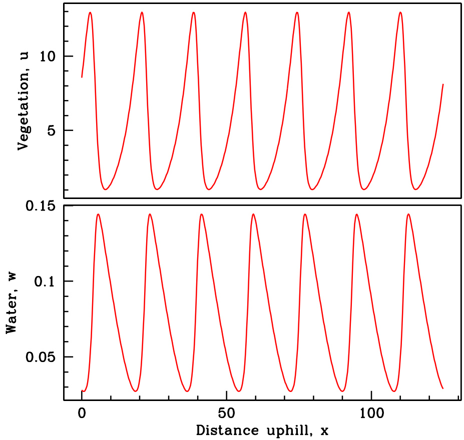
Typical Solution of the Model



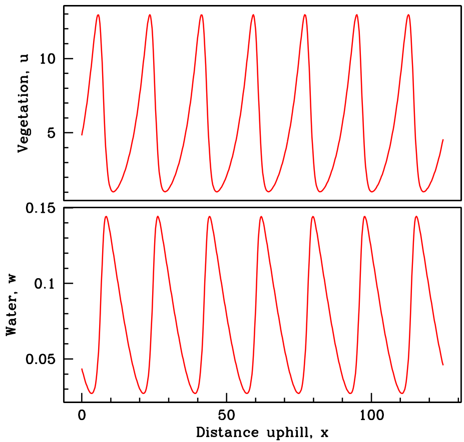
Typical Solution of the Model



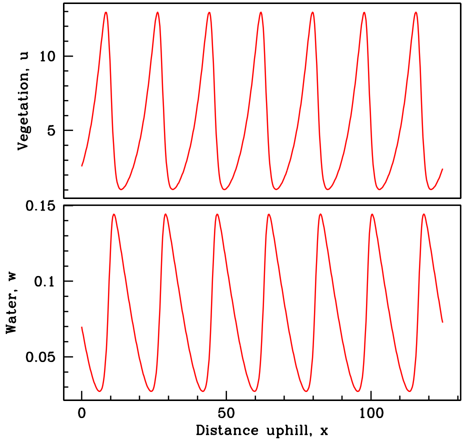
Typical Solution of the Model



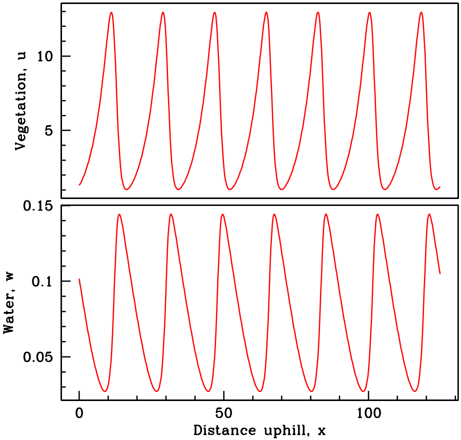
Typical Solution of the Model



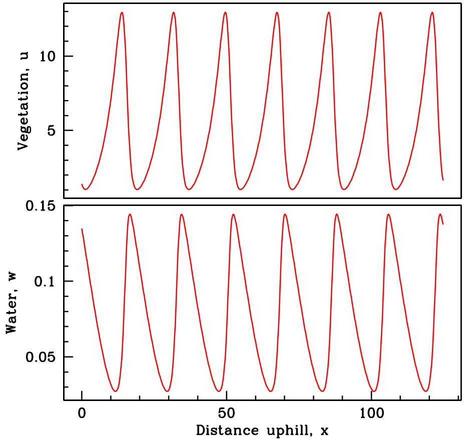
Typical Solution of the Model



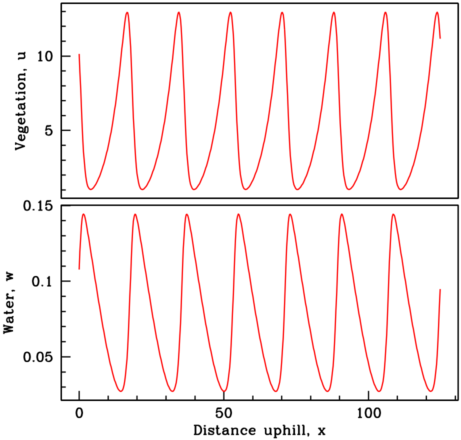
Typical Solution of the Model



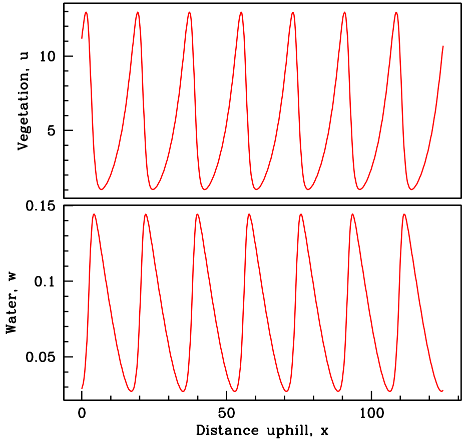
Typical Solution of the Model



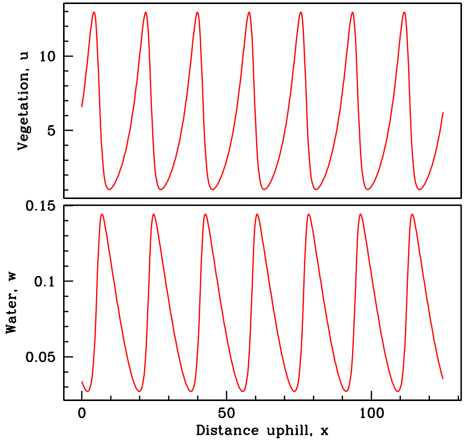
Typical Solution of the Model



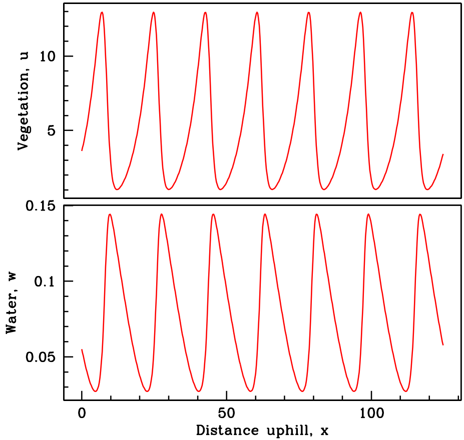
Typical Solution of the Model



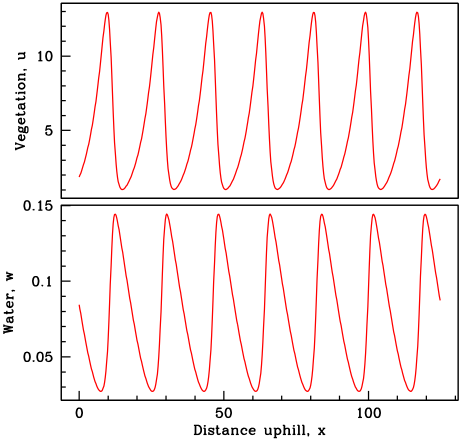
Typical Solution of the Model



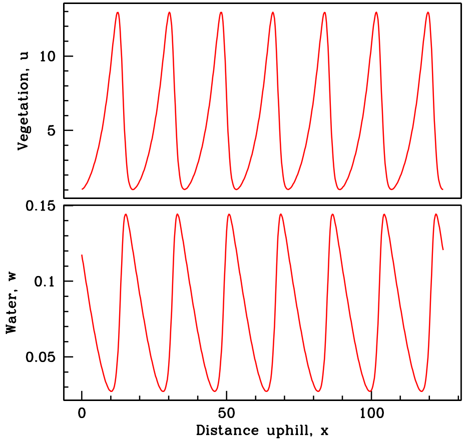
Typical Solution of the Model



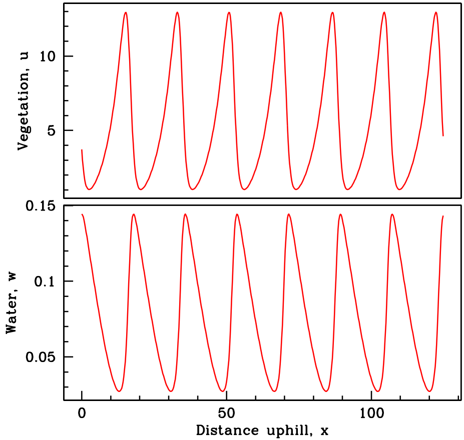
Typical Solution of the Model



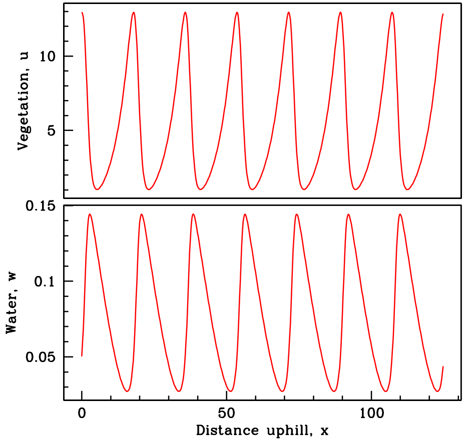
Typical Solution of the Model



Typical Solution of the Model



Typical Solution of the Model



Outline

Homogeneous Steady States

- For all parameter values, there is a stable “desert” steady state $u = 0$, $w = A$

Homogeneous Steady States

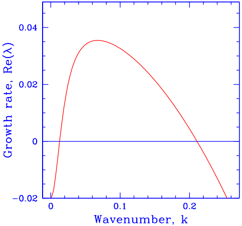
- For all parameter values, there is a stable “desert” steady state $u = 0$, $w = A$
- When $A \geq 2B$, there are also two non-trivial steady states, one of which is unstable to homogeneous perturbations

Homogeneous Steady States

- For all parameter values, there is a stable “desert” steady state $u = 0$, $w = A$
- When $A \geq 2B$, there are also two non-trivial steady states, one of which is unstable to homogeneous perturbations
- Patterns develop when the other steady state (u_s, w_s) is unstable to inhomogeneous perturbations

Approximate Conditions for Patterning

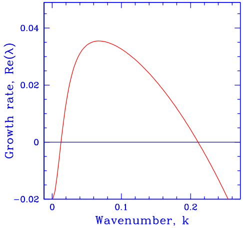
Look for solutions $(u, w) = (u_s, w_s) + (u_0, w_0) \exp\{ikx + \lambda t\}$



The dispersion relation $\mathrm{Re}[\lambda(k)]$ is algebraically complicated

Approximate Conditions for Patterning

Look for solutions $(u, w) = (u_s, w_s) + (u_0, w_0)\exp\{ikx + \lambda t\}$



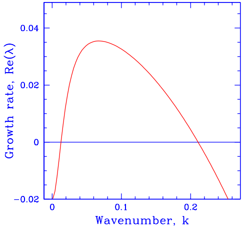
The dispersion relation $\mathrm{Re}[\lambda(k)]$ is algebraically complicated

An approximate condition for pattern formation is

$$A < \nu^{1/2} B^{5/4} / 8^{1/4}$$

Approximate Conditions for Patterning

Look for solutions $(u, w) = (u_s, w_s) + (u_0, w_0) \exp\{ikx + \lambda t\}$



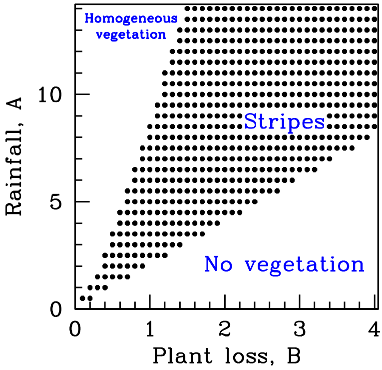
The dispersion relation $\mathrm{Re}[\lambda(k)]$ is algebraically complicated

An approximate condition for pattern formation is

$$2B < A < \nu^{1/2} B^{5/4} / 8^{1/4}$$

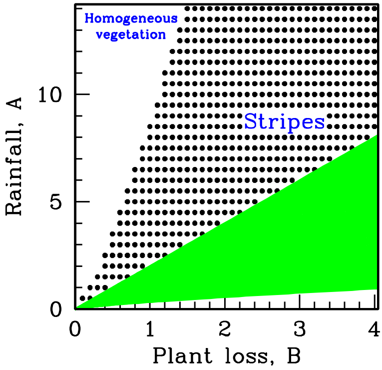
One can niavely assume that existence of (u_s, w_s) gives a second condition

An Illustration of Conditions for Patterning



The dots show parameters for which there are growing linear modes.

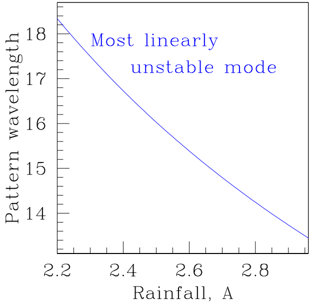
An Illustration of Conditions for Patterning



Numerical simulations show patterns in both the dotted and green regions of parameter space.

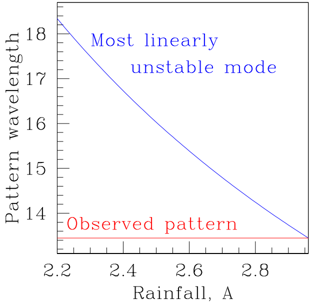
Predicting Pattern Wavelength

Pattern wavelength is the most accessible property of vegetation stripes in the field, via aerial photography. Wavelength can be predicted from the linear analysis.



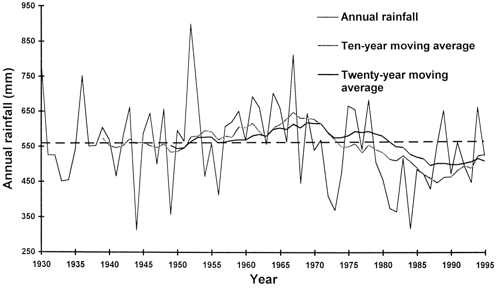
Predicting Pattern Wavelength

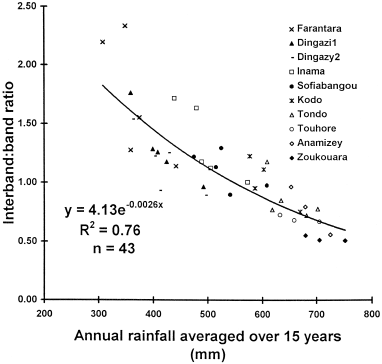
Pattern wavelength is the most accessible property of vegetation stripes in the field, via aerial photography. Wavelength can be predicted from the linear analysis.



However this prediction doesn't fit the patterns seen in numerical simulations.

Data on the Effects of Changing Rainfall





(Data from C. Valentin & J.M. d'Herbès, Catena 37:231, 1999)

Shortcomings of Linear Stability Analysis

Linear stability analysis fails in two ways:

- It significantly over-estimates the minimum rainfall level for patterns.
- Close to the maximum rainfall level for patterns, it incorrectly predicts a variation in pattern wavelength with rainfall.

Outline

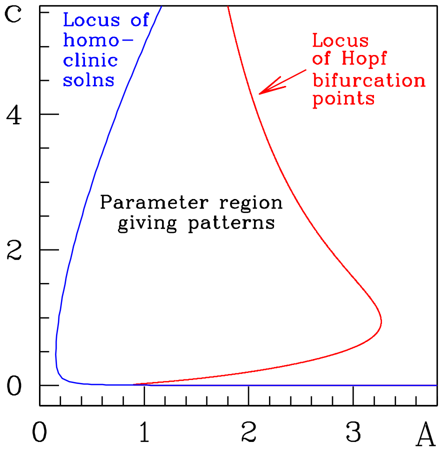
Travelling Wave Equations

The patterns move at constant shape and speed
$\Rightarrow u(x,t) = U(z)$, $w(x,t) = W(z)$, $z = x - ct$

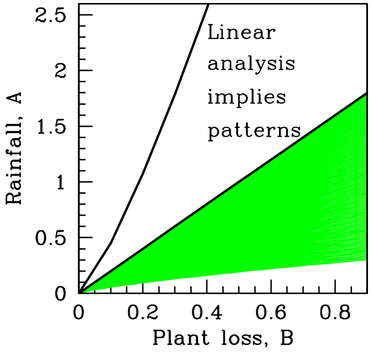
$$\begin{aligned} d^2U/dz^2 + c\,dU/dz + WU^2 - BU &= 0 \\ (\nu + c)dW/dz + A - W - WU^2 &= 0 \end{aligned}$$

The patterns are periodic (limit cycle) solutions of these equations

When do Patterns Form?

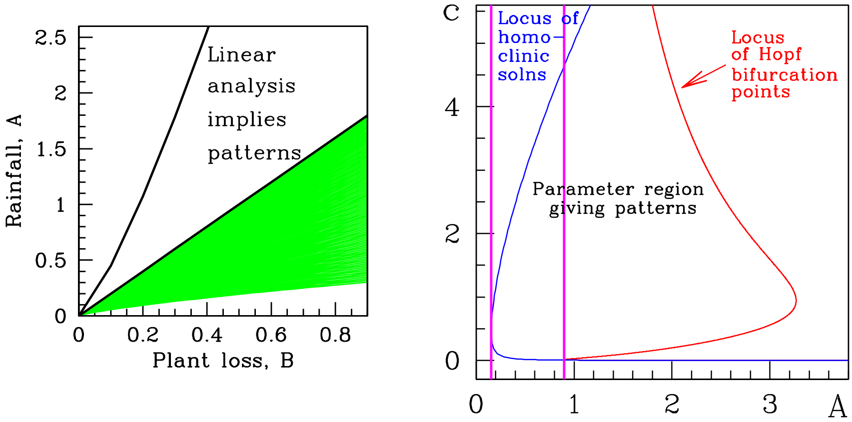


Pattern Formation for Low Rainfall

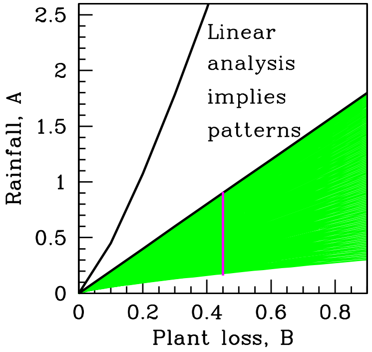


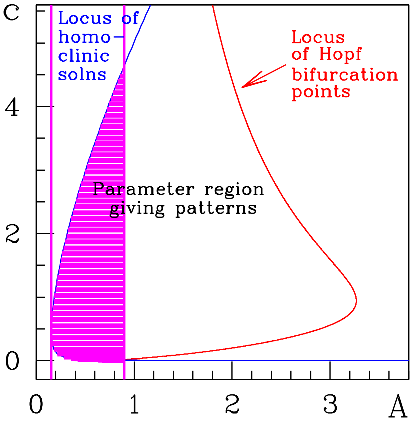
Patterns are also seen for parameters in the green region.

Pattern Formation for Low Rainfall

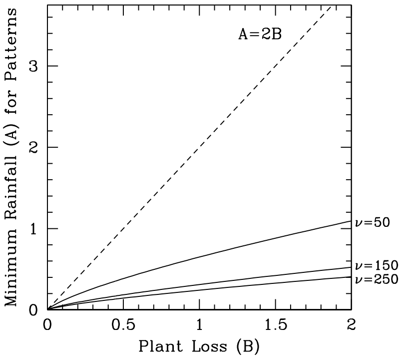


Pattern Formation for Low Rainfall



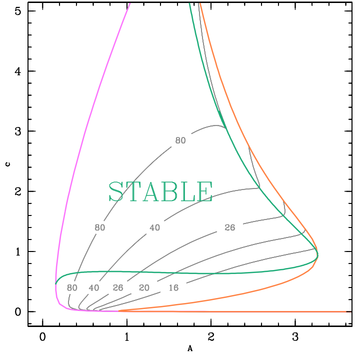


Minimum Rainfall for Patterns



Pattern Stability

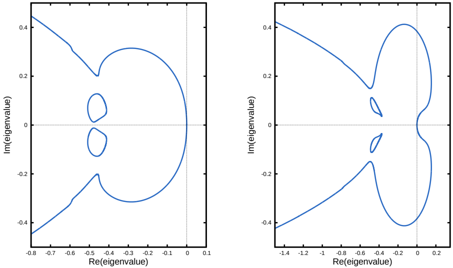
Not all of the possible patterns are stable as solutions of the model equations.



The wavelengths shown are those compatible with periodic boundary conditions on a domain of length 80.

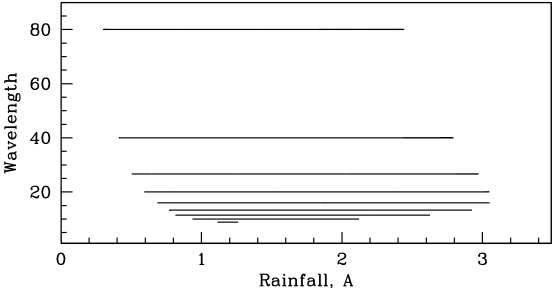
Pattern Stability: Numerical Approach

The boundary between stable and unstable patterns can be calculated by numerical continuation of the essential spectrum.



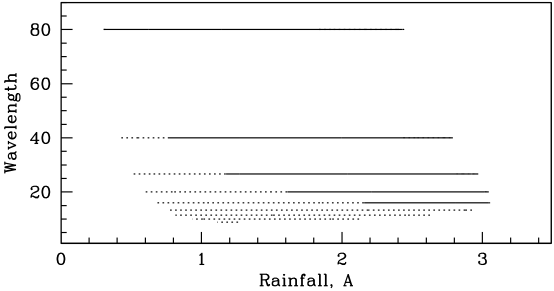
Calculations of this type can be performed using the software package WAVETRAIN (www.ma.hw.ac.uk/wavetrain).

Pattern Stability: Wavelength vs Rainfall



The wavelengths shown are those compatible with periodic boundary conditions on a domain of length 80.

Pattern Stability: Wavelength vs Rainfall



The wavelengths shown are those compatible with periodic boundary conditions on a domain of length 80.

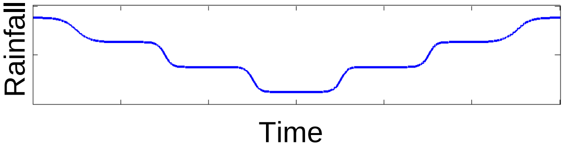
Pattern Stability: Key Result

Key Result

Many of the possible patterns are unstable and thus will never be seen.

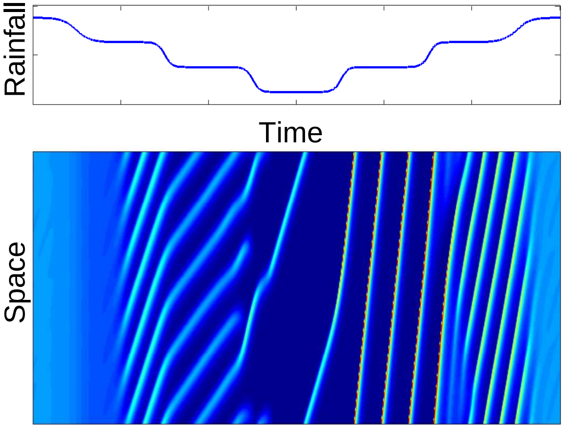
However, for a wide range of rainfall levels, there are multiple stable patterns.

Hysteresis



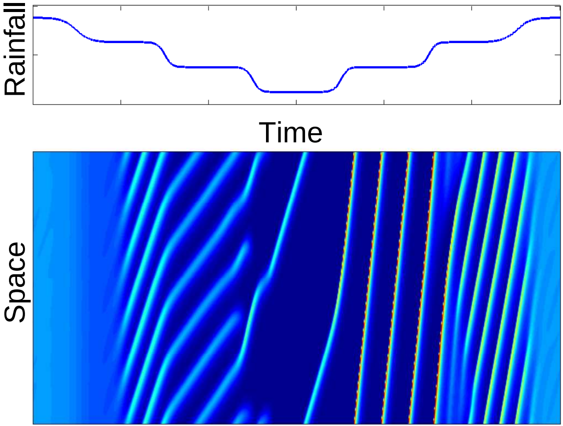
- The existence of multiple stable patterns raises the possibility of hysteresis
- We consider slow variations in the rainfall parameter A
- Parameters correspond to grass, and the rainfall range corresponds to 130–930 mm/year

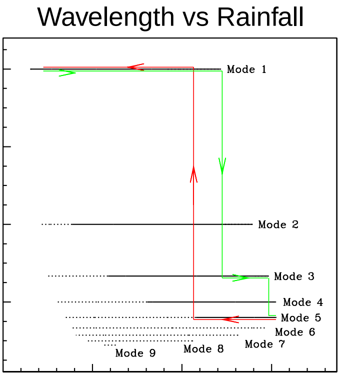
Hysteresis



<< Mode 5 >> <<<<< Mode 1 >>>>> < Mode 3 >

Hysteresis



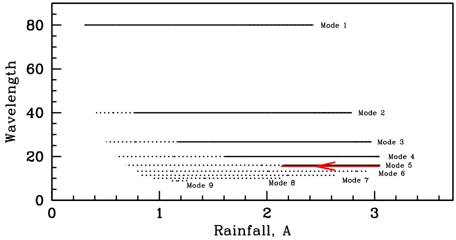


<< Mode 5 >> <<<<< Mode 1 >>>>> < Mode 3 >

Outline

Predictions of Pattern Wavelength

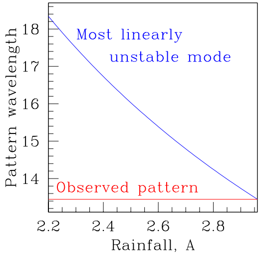
- In general, pattern wavelength depends on initial conditions
- When vegetation stripes arise from homogeneous vegetation via a decrease in rainfall, pattern wavelength will remain at its bifurcating value.



Predictions of Pattern Wavelength

- In general, pattern wavelength depends on initial conditions
- When vegetation stripes arise from homogeneous vegetation via a decrease in rainfall, pattern wavelength will remain at its bifurcating value.

$$\text{Wavelength} = \sqrt{\frac{8\pi^2}{B\nu}}$$



References

J.A. Sherratt: An analysis of vegetation stripe formation in semi-arid landscapes. *J. Math. Biol.* 51, 183-197 (2005).

J.A. Sherratt, G.J. Lord: Nonlinear dynamics and pattern bifurcations in a model for vegetation stripes in semi-arid environments. *Theor. Pop. Biol.* 71, 1-11 (2007).

J.A. Sherratt: Pattern solutions of the Klausmeier model for banded vegetation in semi-arid environments I. *Nonlinearity* 23, 2657-2675 (2010).

J.A. Sherratt: Pattern solutions of the Klausmeier model for banded vegetation in semi-arid environments II. Patterns with the largest possible propagation speeds. *Proc. R. Soc. Lond.* A in press.

J.A. Sherratt: Pattern solutions of the Klausmeier model for banded vegetation in semi-arid environments III. The transition between homoclinic solutions. Submitted.

List of Frames