Precipitation variability and dryland vegetation

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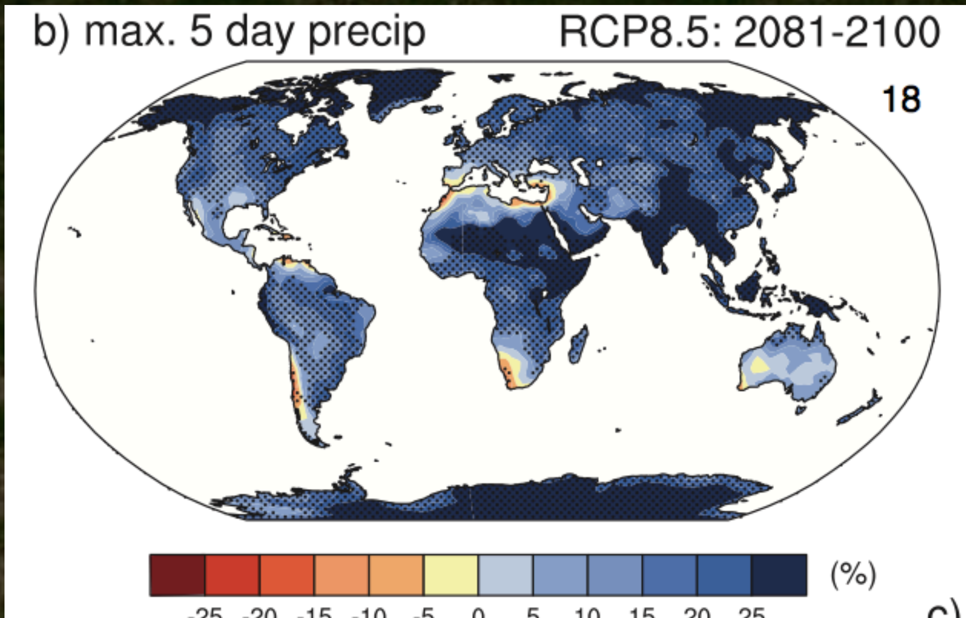
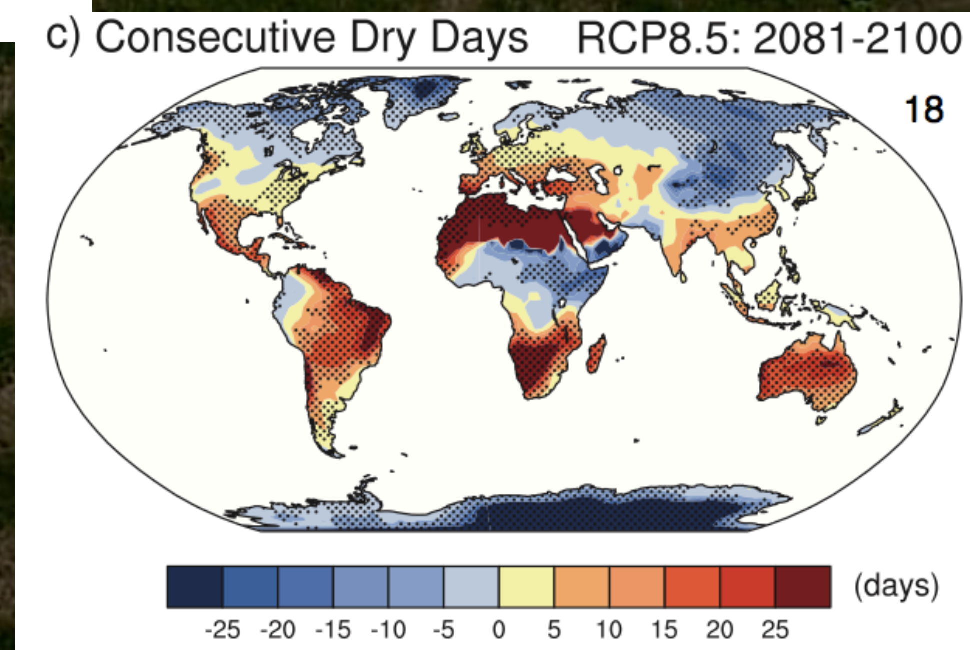
Projected changes in precipitation intensity and variability



CMIP5
global climate models,
in the RCP 8.5 scenario



From: IPCC 5th assessment report, Climate Change 2013, ch. 12

- What is the impact of precipitation variability on the spatial distribution and on the dynamics of dryland vegetation?

- In particular precipitation in drylands is highly intermittent: What is the role of vegetation feedbacks in this context?

- What are the impacts on evapotranspirative fluxes?

- We can use simple mathematical models to study these issues

Intermittent precipitation

We model intermittent precipitation as a stochastic Poisson process:

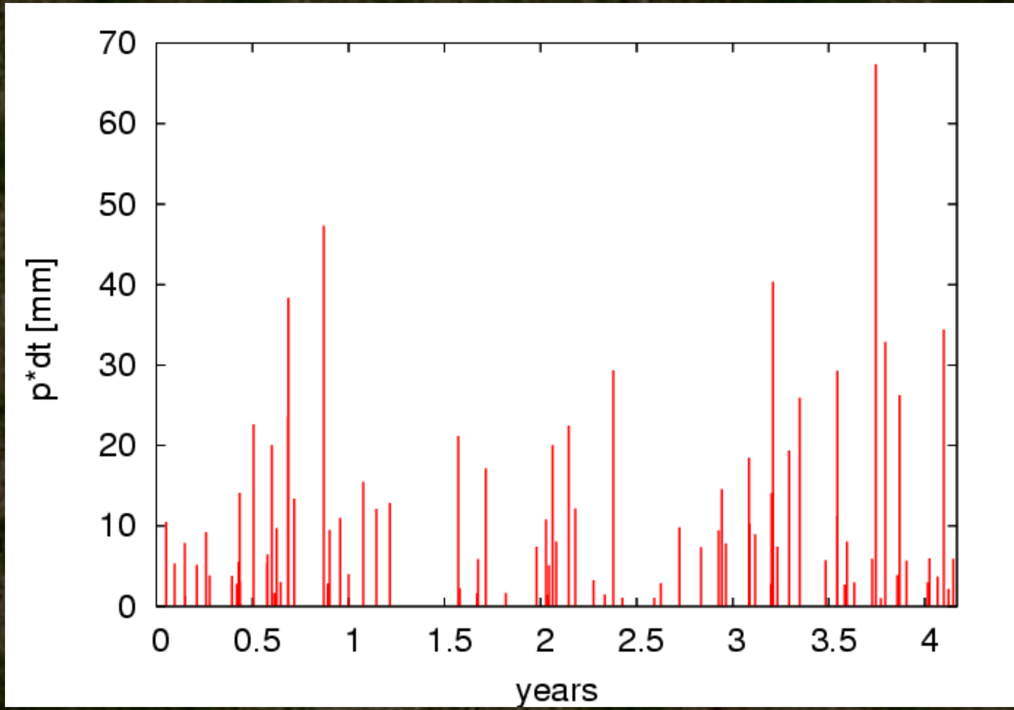
Exponential distribution both for the precipitation event amplitudes, h, and for interarrival times τ

$$f_\tau(\tau) = \lambda e^{-\lambda\tau}$$

$$f_H(h) = \frac{1}{\alpha} e^{-\frac{1}{\alpha}h}$$

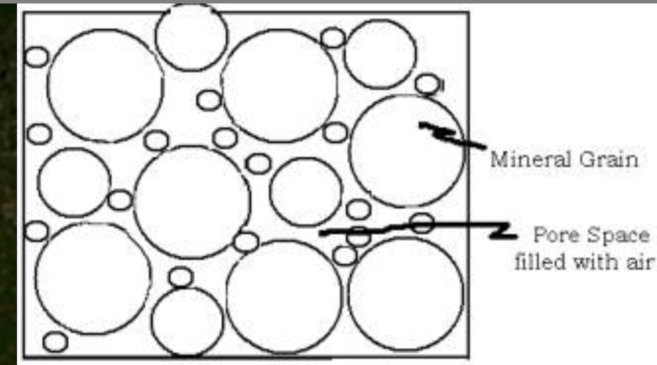
Short precipitation events Δt=8h

(Rodriguez – Iturbe *et al.*, 1999)



No interannual variability, same distribution of events repeated every year (but random timing)

Relative soil humidity



- Soil= mineral+water+air:

$$V_s = V_a + V_w + V_m$$

- Porosity:

$$n = \frac{V_a + V_w}{V_s}$$

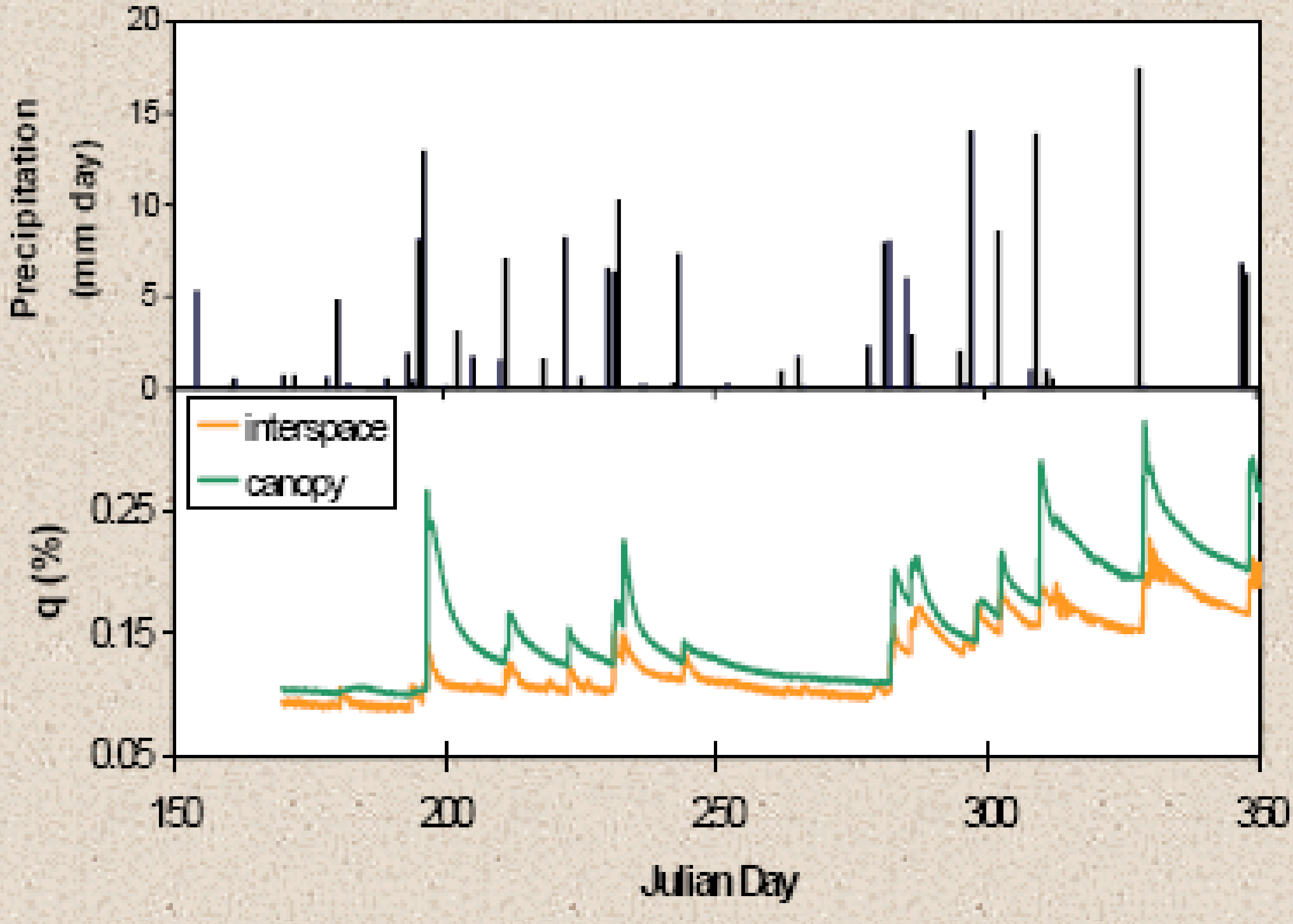
- Volumetric soil humidity:

$$\mu = \frac{V_w}{V_s}$$

- Relative soil humidity:

$$s = \frac{\mu}{n}$$

Dynamics of soil humidity



Sevilleta,

New Mexico

An ecohydrological model for soil humidity dynamics

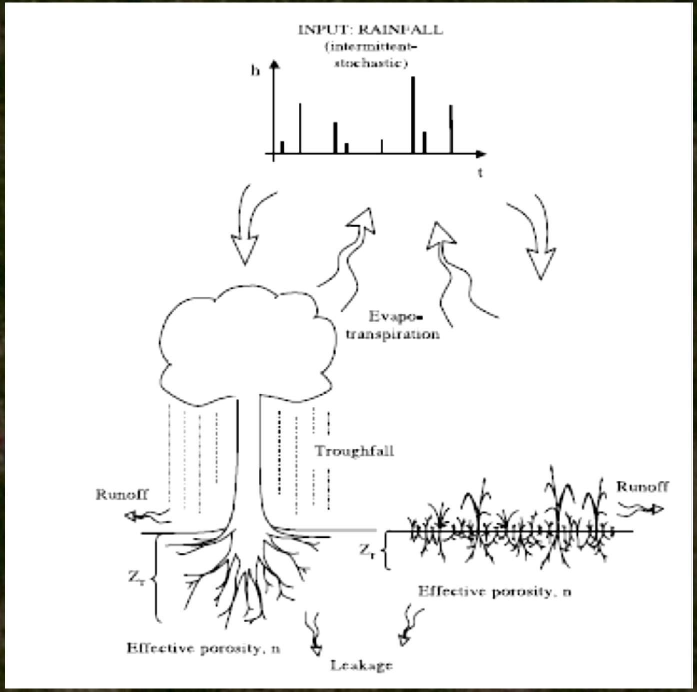
Dynamics of relative humidity in a soil layer of depth Z_r :

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \frac{1}{nZ_r}\left[\varphi(s,r) - \chi(s)\right] = I(s,r) - X(s)$$

n porosity
Z_r active soil layer depth

nZ_r : depth available for water accumulation

s relative soil humidity
$\phi(s, t)$ rainfall infiltration rate
$X(s)$ evapotranspiration and percolation rate

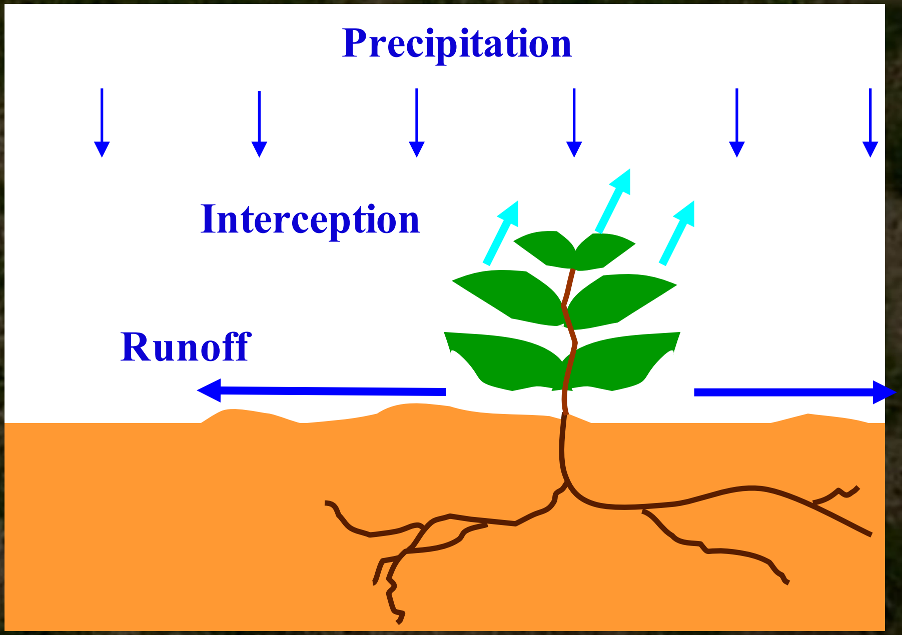


(Rodriguez – Iturbe et al., 1999
Porporato et al., 2002)

Soil infiltration

$$\varphi[s(t);t] = R(t) - I(t) - Q[s(t);t]$$

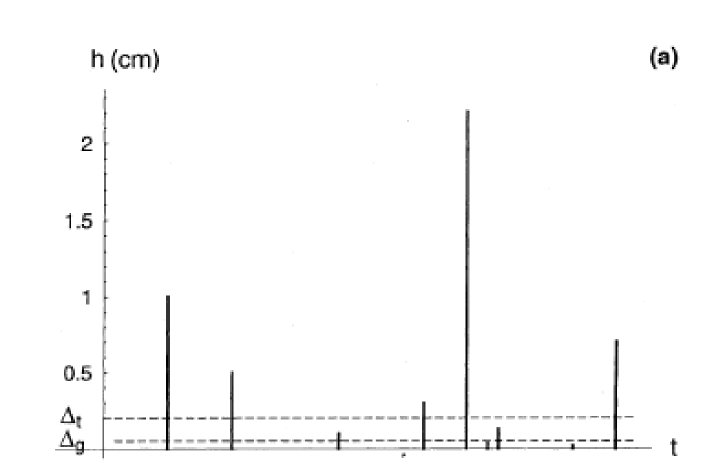
R(t): Precipitation rate
I(t): loss due to leaf interception
Q(t): runoff rate



Leaf interception of rainfall

Threshold below which water does not reach the ground

Changes the average interarrival time of events ($\lambda' < \lambda$ less frequent events)



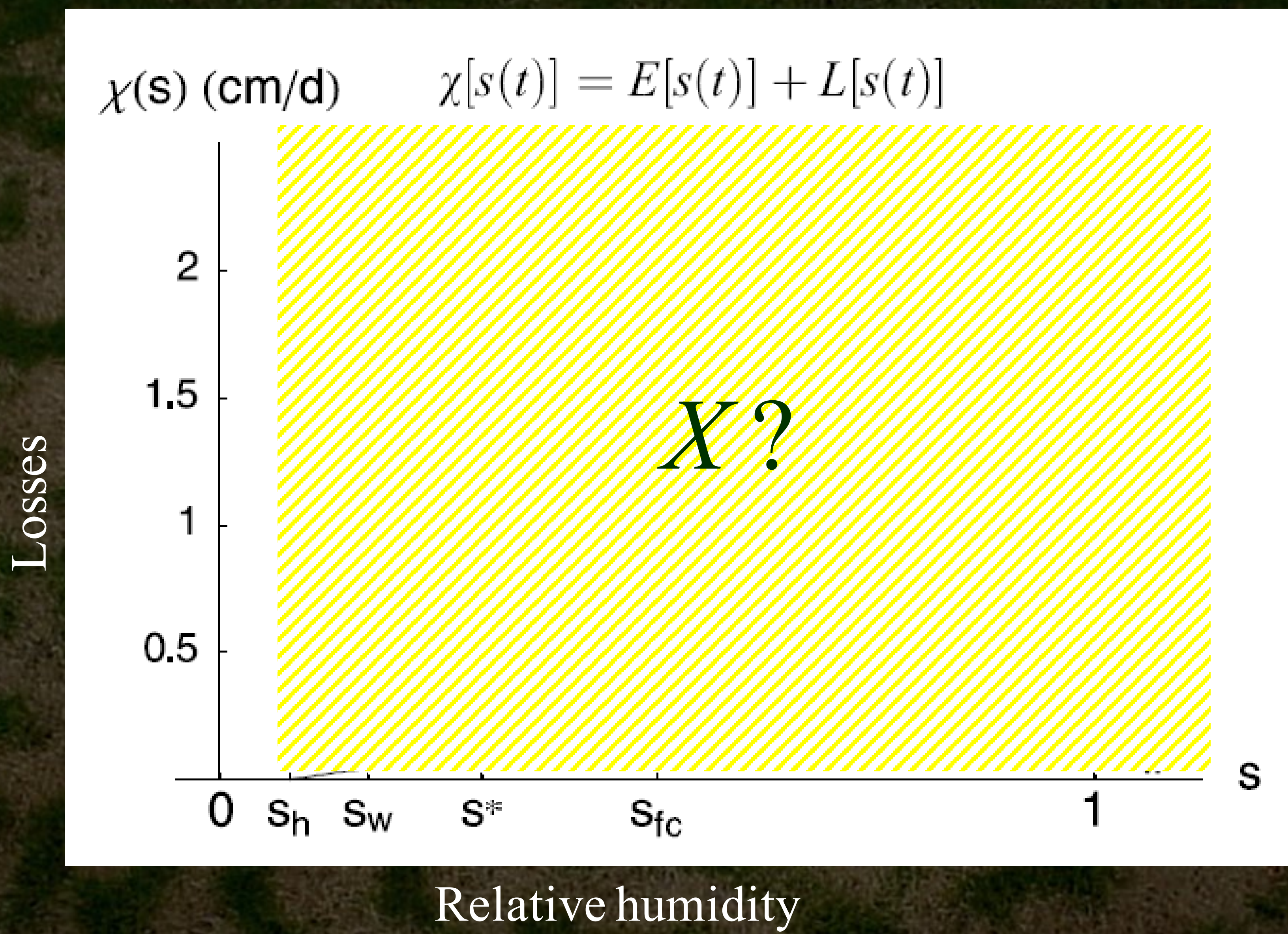
$$\lambda' = \lambda e^{-\Delta/\alpha}$$

Infiltration

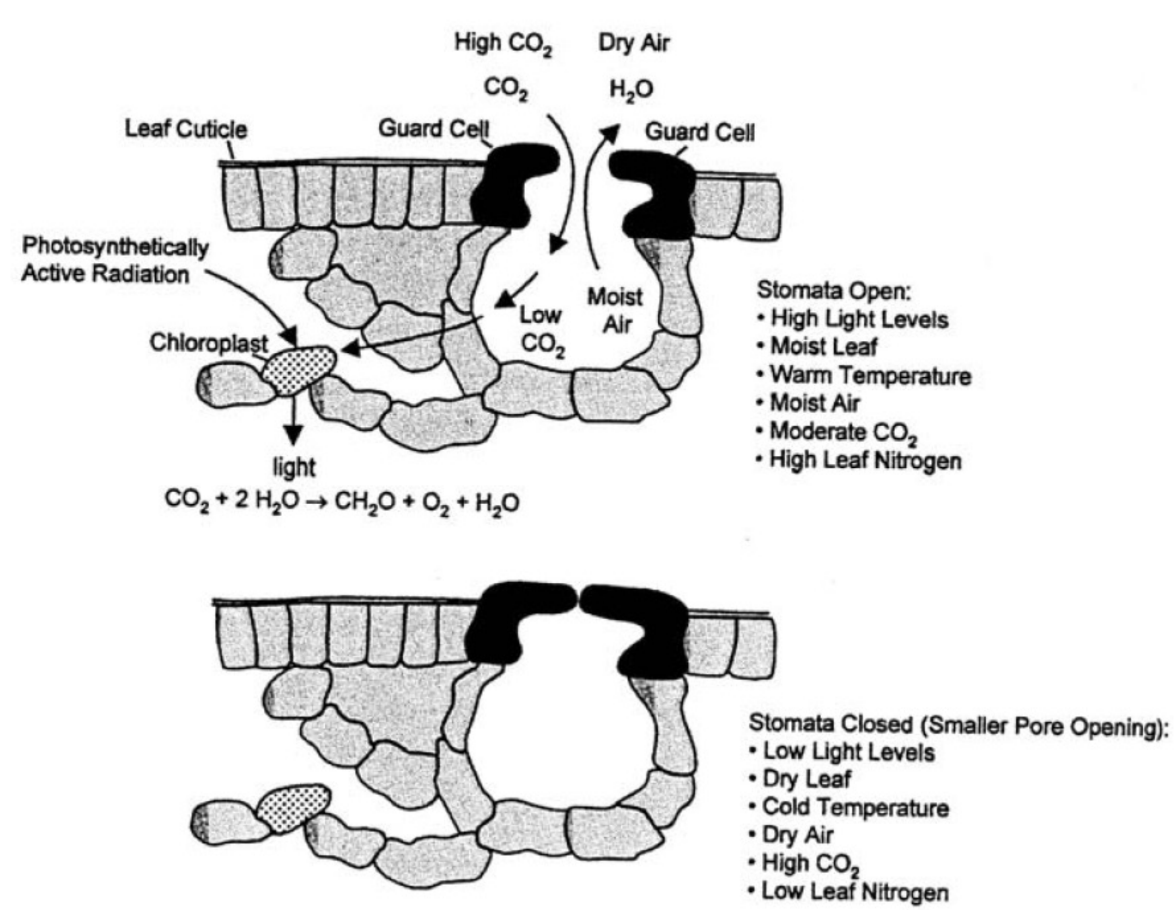
Infiltration: minimum between not intercepted precipitation and soil capability to absorb rainfall (runoff occurs beyond saturation)

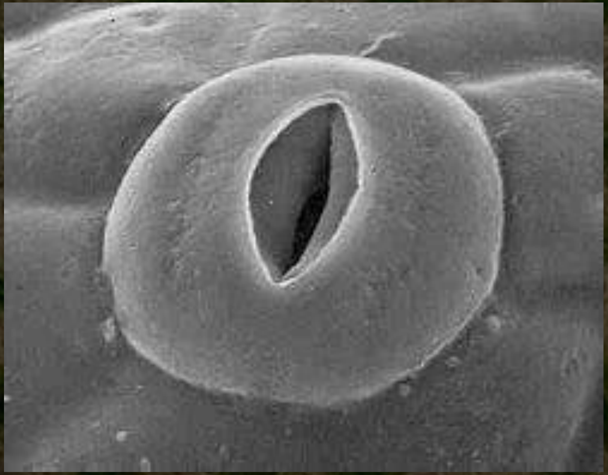
$$I = \begin{cases} \frac{r}{nZ_r} & \text{if } \frac{r\Delta t}{nZ_r} < 1 - s \\ \frac{1-s}{\Delta t} & \text{if } \frac{r\Delta t}{nZ_r} \geqslant 1 - s \end{cases}$$

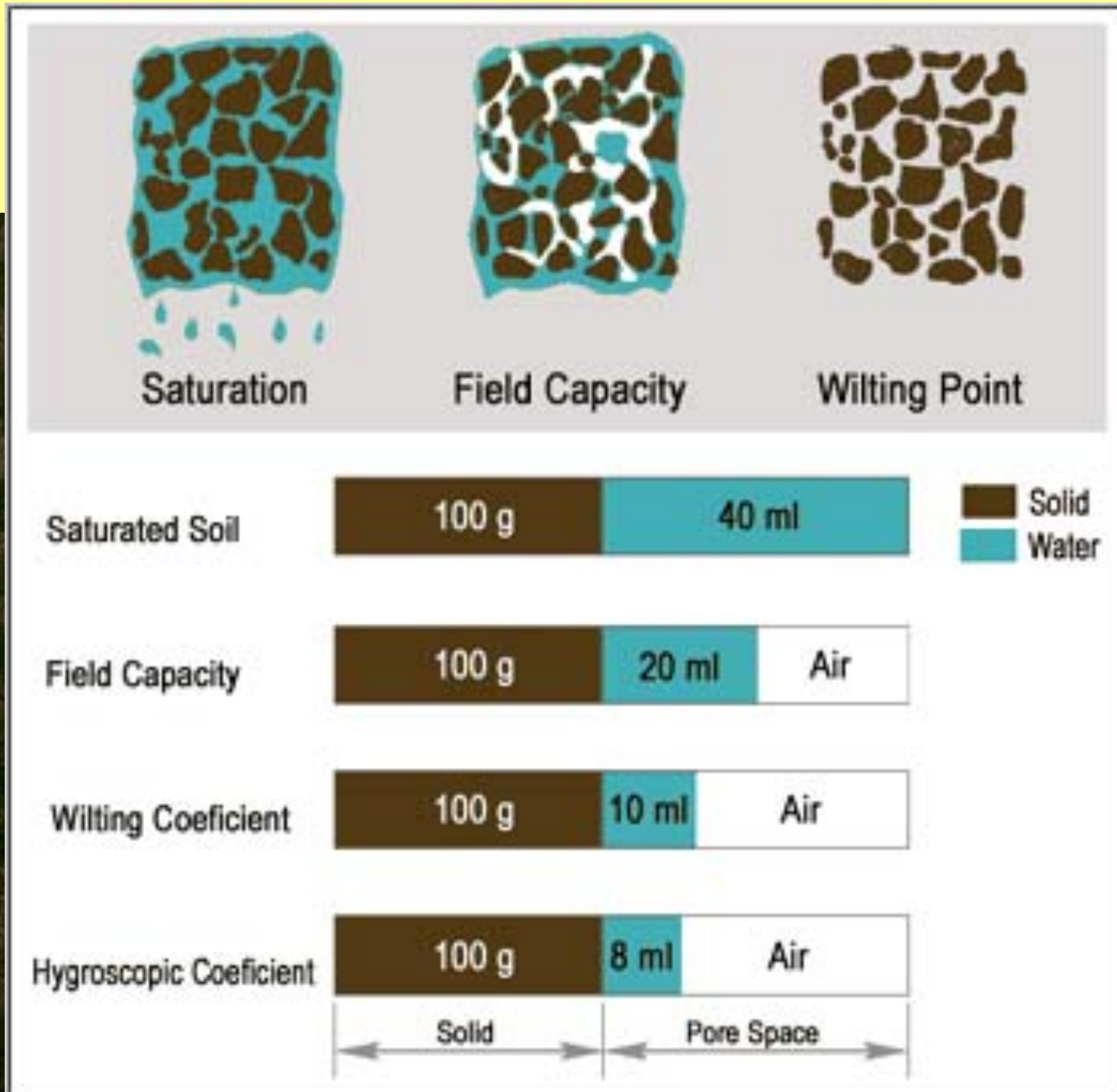
Losses: evapotranspiration + percolation



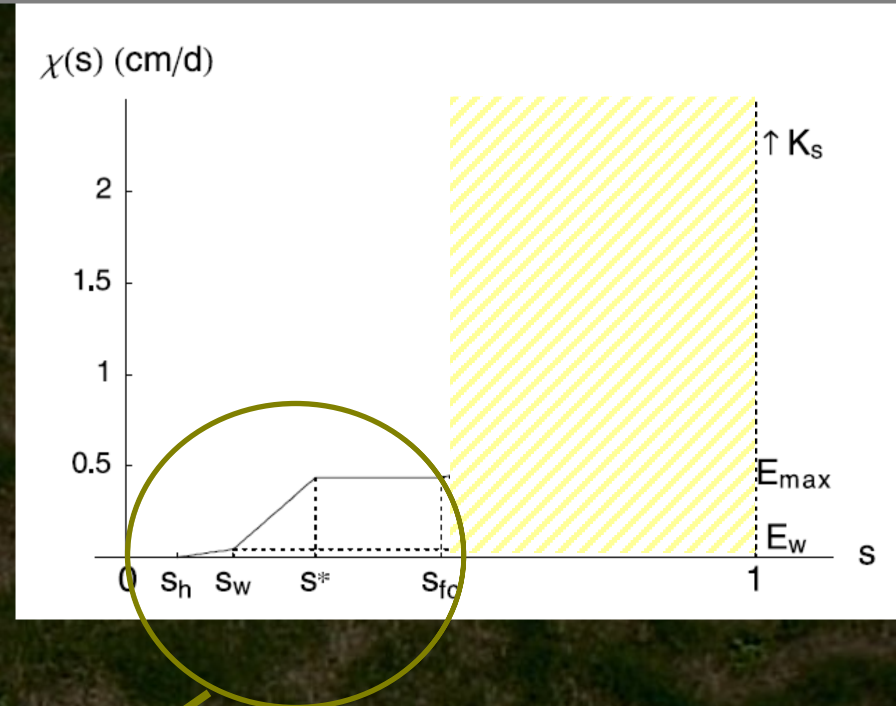
Transpiration

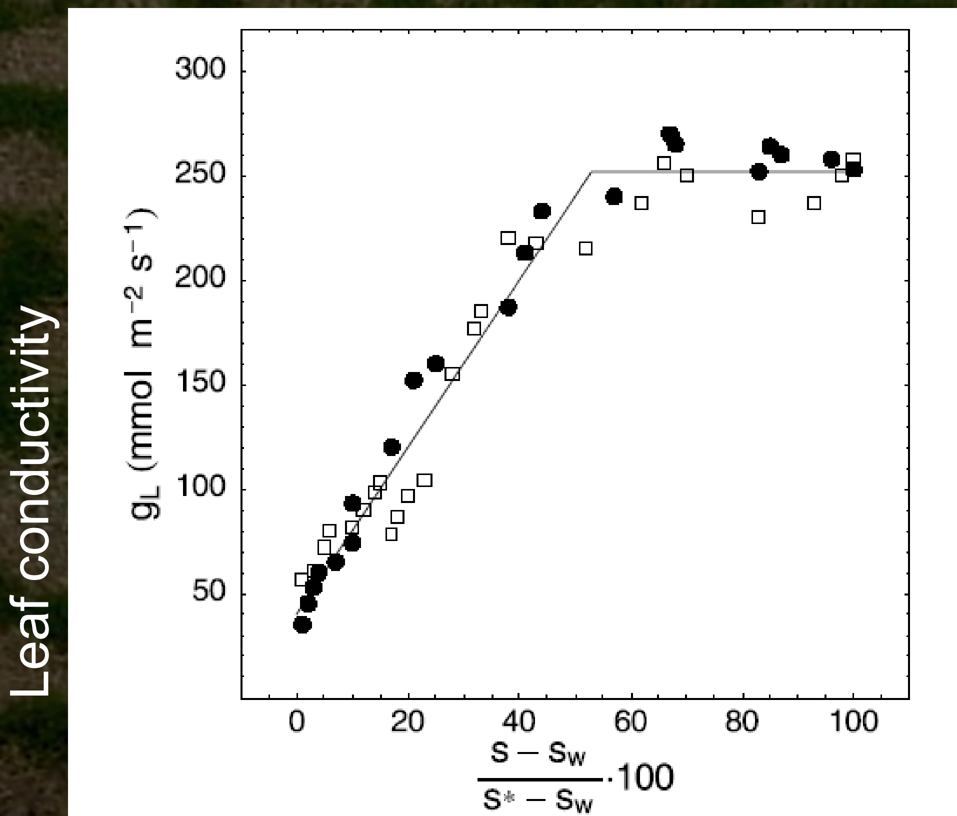





Saturation
Field Capacity
Wilting Point
Saturated Soil
100 g
40 ml
Solid
Water
Field Capacity
100 g
20 ml
Air
Wilting Coeficient
100 g
10 ml
Air
Hygroscopic Coeficient
100 g
8 ml
Air
Solid
Pore Space

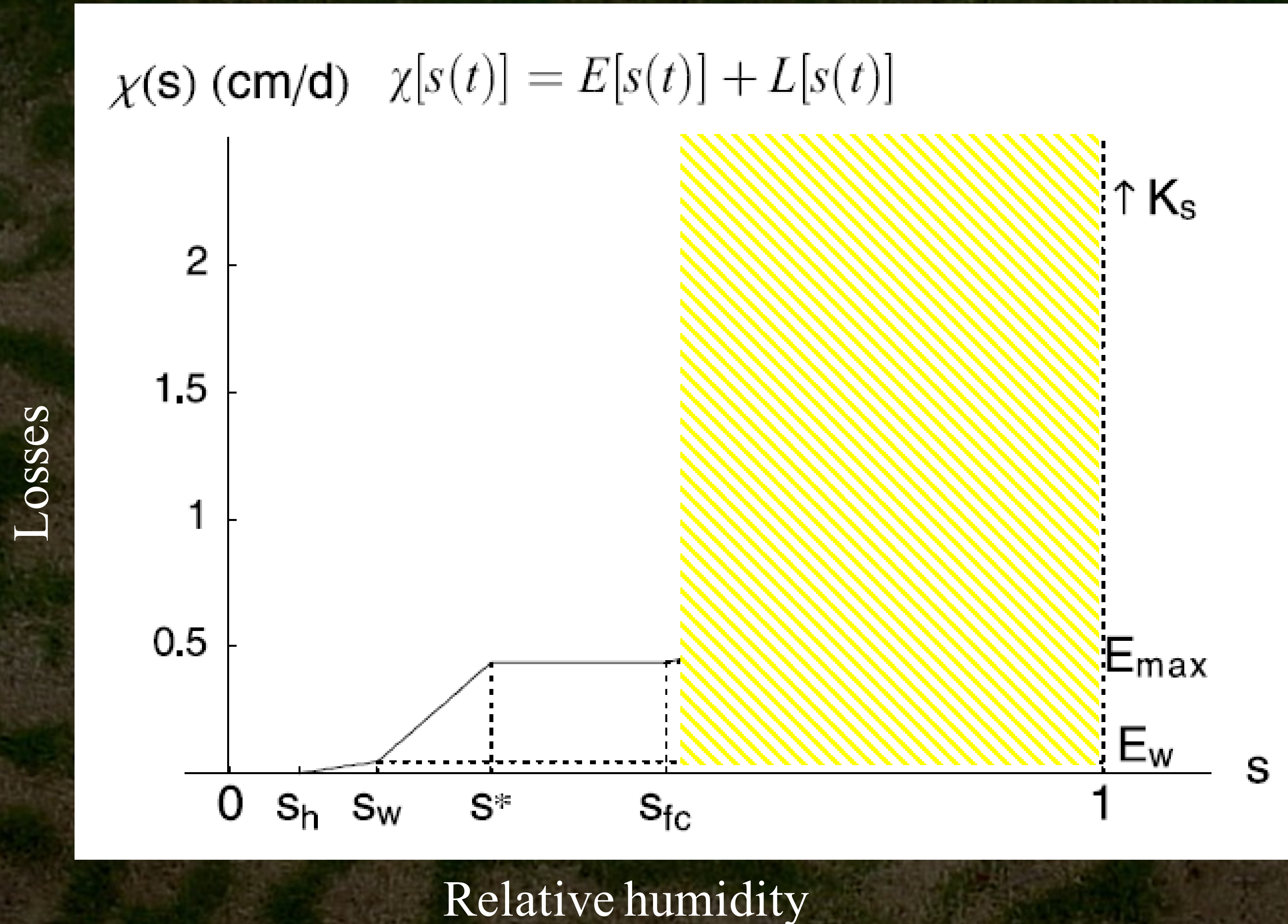
Evapotranspiration





s^* and s_w depend on plant and on soil type

Losses: evapotranspiration + percolation



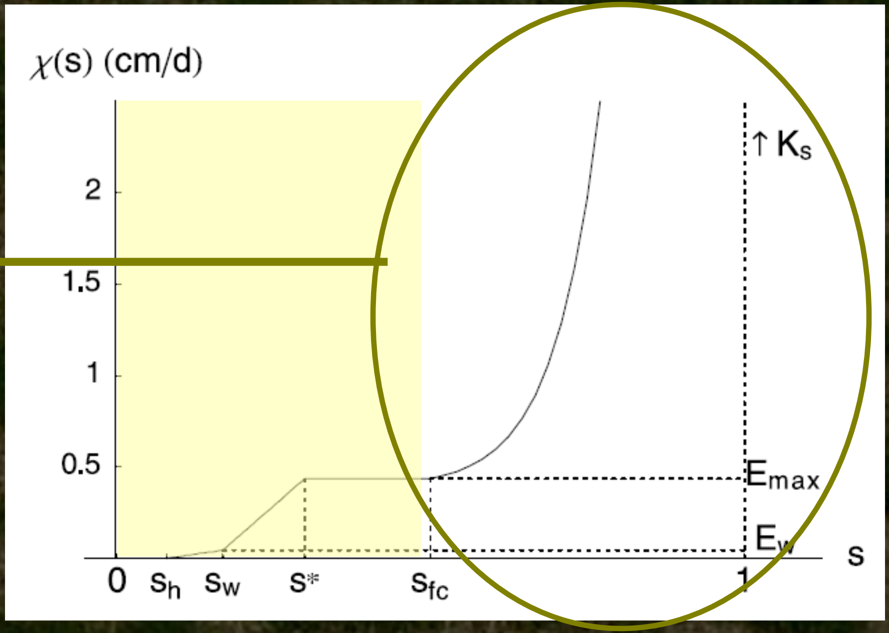
Parameters: E_{max}, s*, s_w

Percolation losses

Gravity losses: maximum at saturation, decay quickly at lower s values, down to 0 at the field capacity S_{fc}

$$K(s) = L(s) = \frac{K_s}{e^{\beta(1-s_{fc})} - 1}\left[e^{\beta(s-s_{fc})} - 1\right]$$

for $s_{fc} < s < 1$



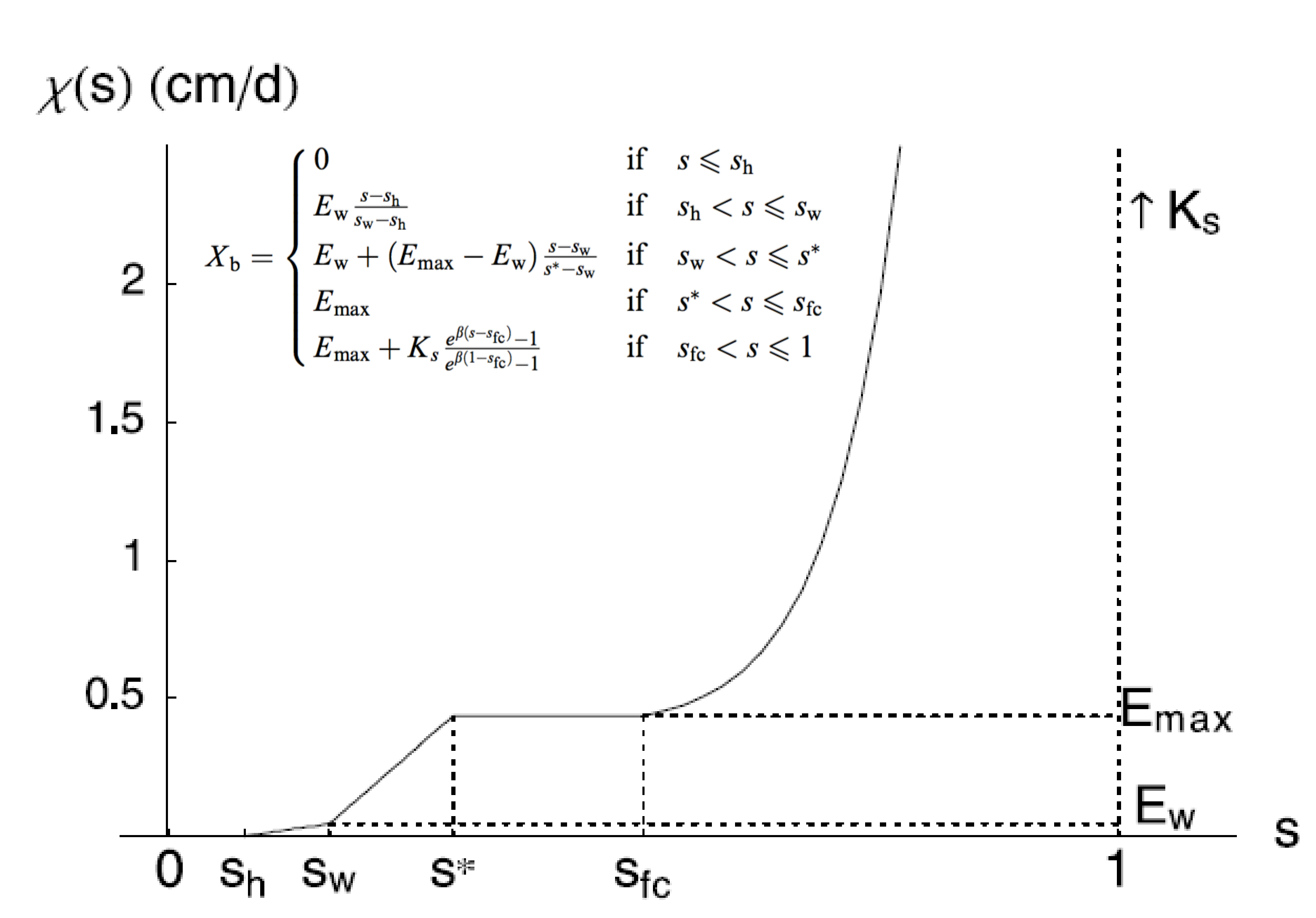
s_{fc} **field capacity:** defined as the value of s at which percolation losses become negligible compared to evapotranspiration.

K_s saturated hydraulic conductivity

β parameter which depends on the soil type

Losses: evapotranspiration + percolation

Losses

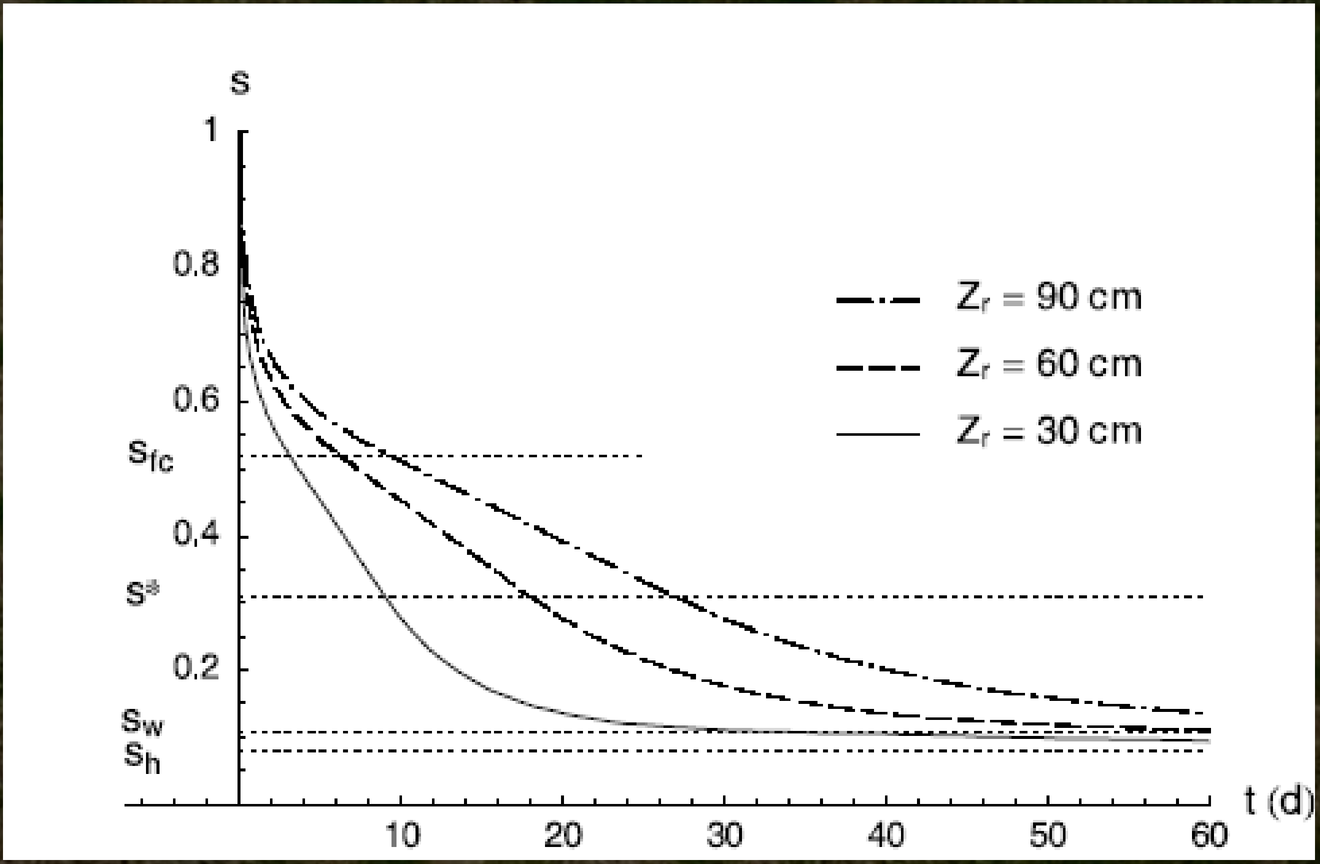


Relative humidity

Rodriguez-Iturbe I, Porporato A. Ecohydrology of water controlled ecosystems: soil moisture and plant dynamics. Cambridge: Cambridge University Press; 2005.

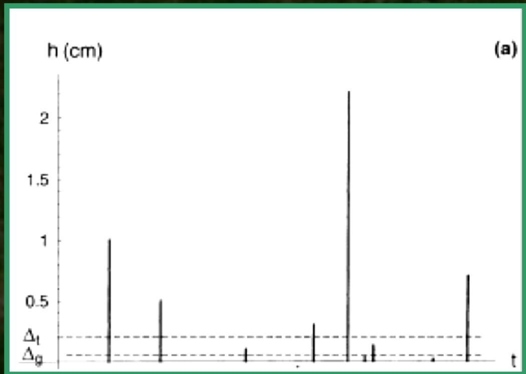
Parameters: E_{max}, s^*, s_w

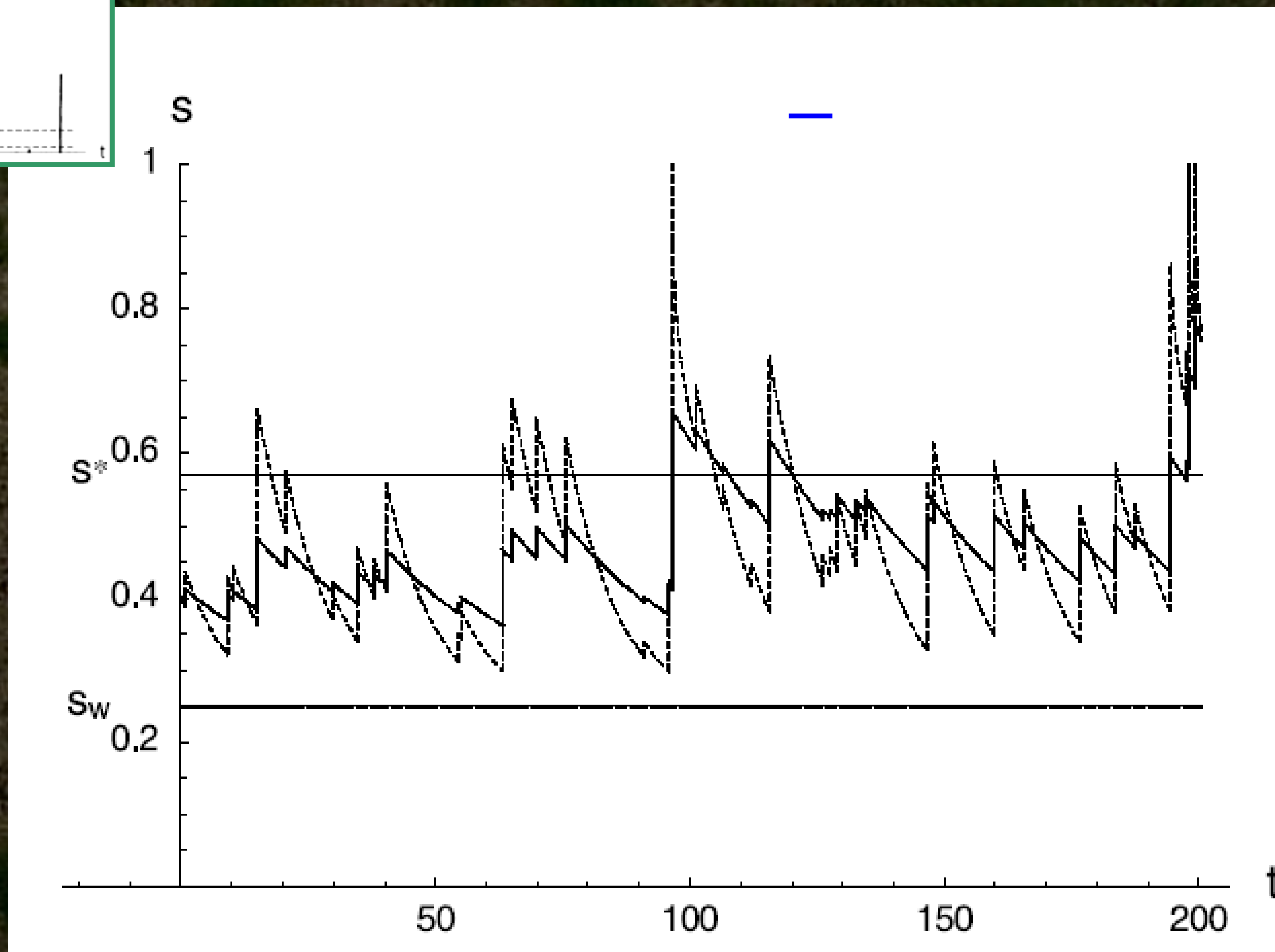
Analytical solutions after a precipitation event



(Porporato et al., 2002)

Soil humidity dynamics





Less deep soil

more extreme s values

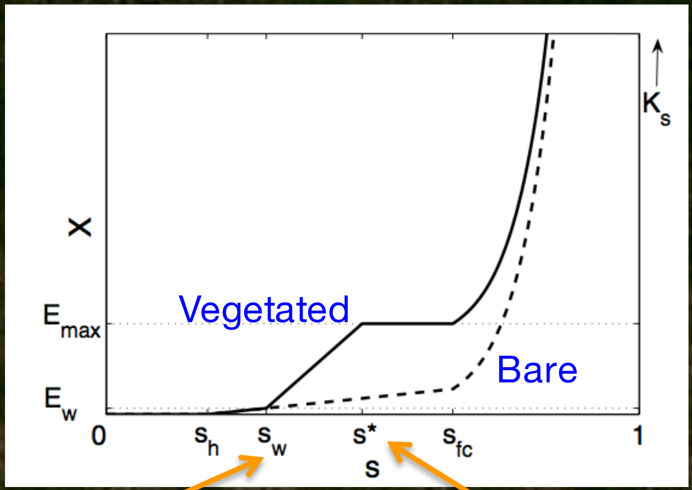
A simple ecohydrological model

1) A simple box model for soil moisture dynamics

$$\frac{\mathrm{d}s}{\mathrm{d}t} = I(s,r) - X(s)$$

$$I = \begin{cases} \frac{r}{nZ_r} & \text{if } \frac{r\Delta t}{nZ_r} < 1 - s \\ \frac{1-s}{\Delta t} & \text{if } \frac{r\Delta t}{nZ_r} \geqslant 1 - s \end{cases}$$

From: Laio et al. *Adv Water Res* 24:707–23 (2001)



S_w : wilting point

S^* : stomata fully open

Ref: Baudena M., Boni G., Ferraris L., von Hardenberg J., Provenzale A., *Advances in Water Resources* **30**(50), 1320-28 (2007)

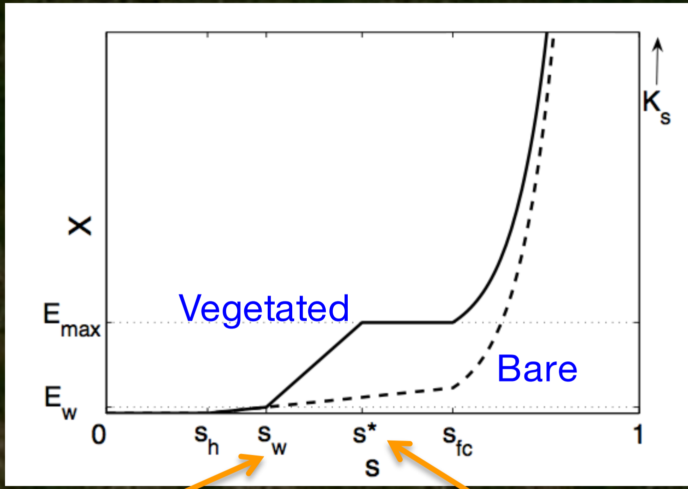
A simple ecohydrological model

1) A simple box model for soil moisture dynamics

$$\frac{\mathrm{d}s}{\mathrm{d}t} = I(s,r) - [bX_b(s) + (1-b)X_0(s)]$$

$$I = \begin{cases} \frac{r}{nZ_r} & \text{if } \frac{r\Delta t}{nZ_r} < 1 - s \\ \frac{1-s}{\Delta t} & \text{if } \frac{r\Delta t}{nZ_r} \geqslant 1 - s \end{cases}$$

From: Laio et al. *Adv Water Res* 24:707–23 (2001)



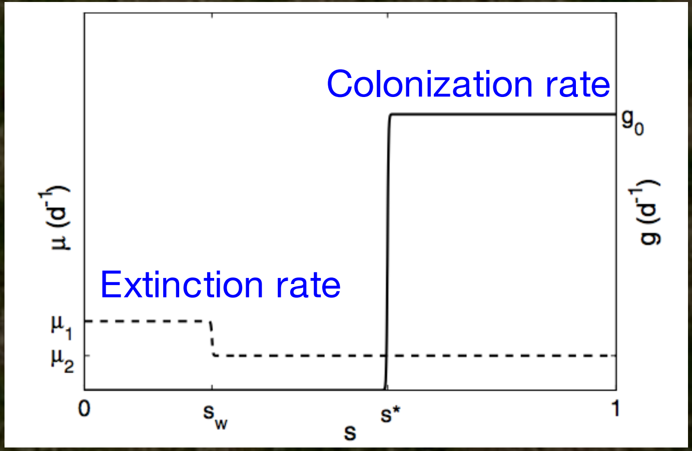
S_w : wilting point

S^* : stomata fully open

2) An implicit-space representation of vegetation cover

$$\frac{\mathrm{d}b}{\mathrm{d}t} = g(s)b(1-b) - \mu(s)b$$

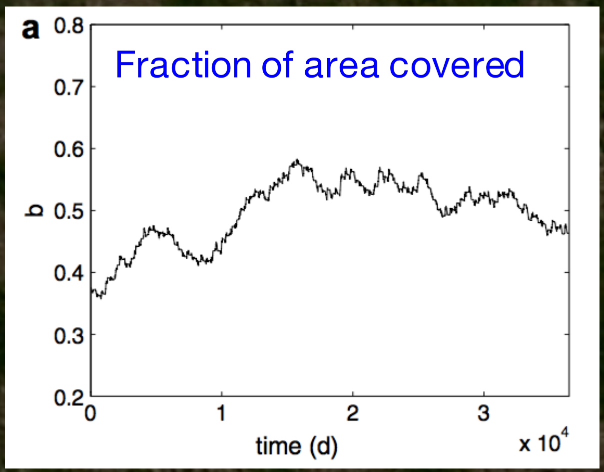
b : Fractional vegetation cover
s : average relative soil humidity

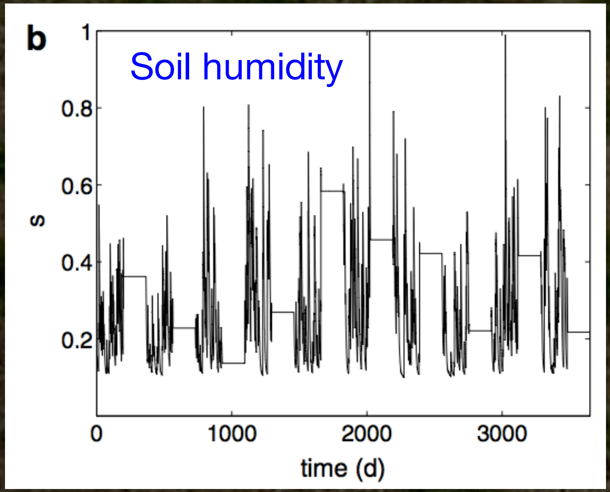


Ref: Baudena M., Boni G., Ferraris L., von Hardenberg J., Provenzale A., *Advances in Water Resources* **30**(50), 1320-28 (2007)

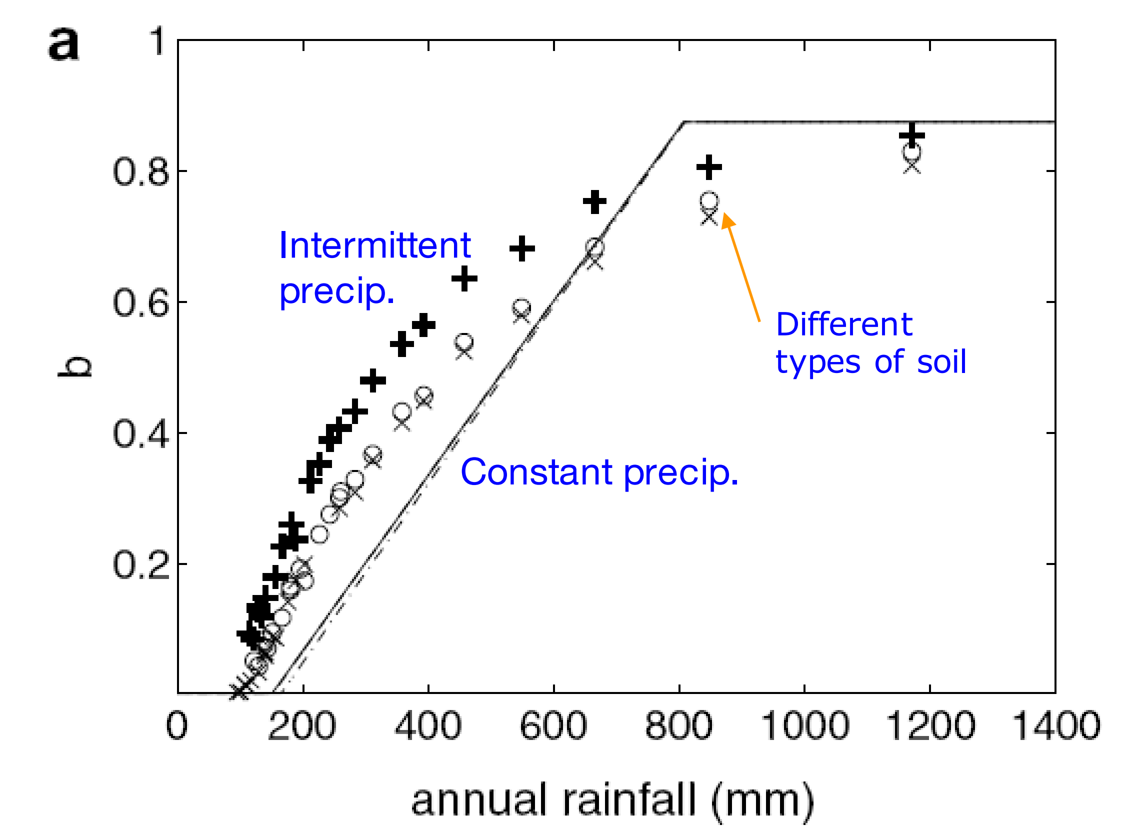
Vegetation persistence in a simple ecohydrological model

(With a ‘frozen’ dry season)





Fraction of area covered

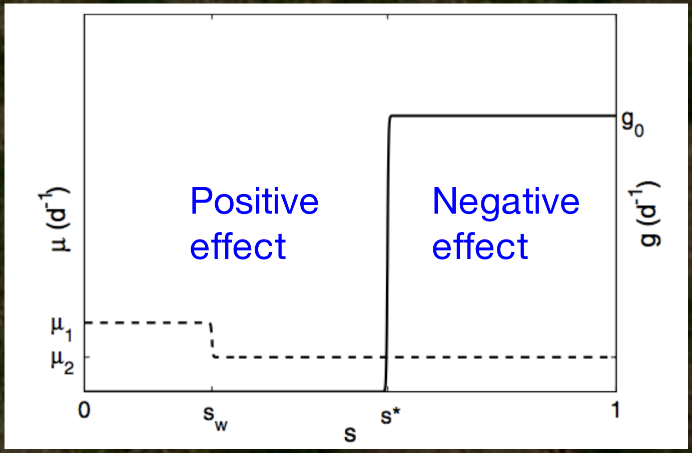


Jensen's inequality

How can fluctuations in soil moisture be beneficial for vegetation?

$$\overline{g(s)} = \overline{g(\bar{s}+\delta s)} \approx g(\bar{s}) + \frac{1}{2}\left(\frac{\mathrm{d}^2 g}{\mathrm{d}s^2}\right)_{s=\bar{s}} \overline{(\delta s)^2}$$

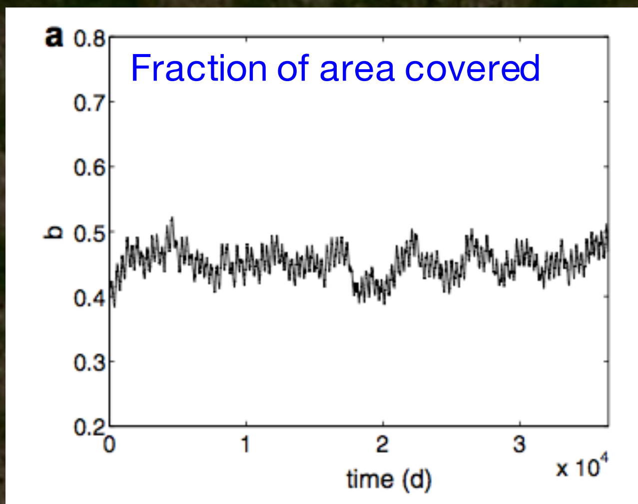
The average colonization rate in the presence of fluctuations is larger than the colonization rate corresponding to the average soil moisture
if g(s) has a positive second derivative
(a concave-up form)

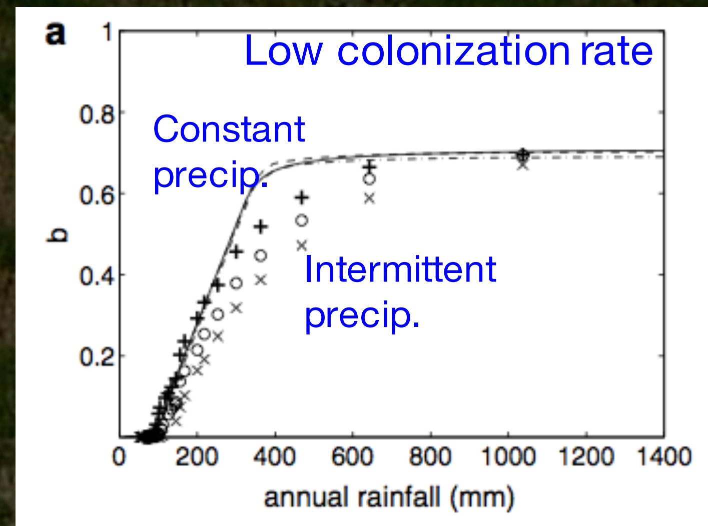


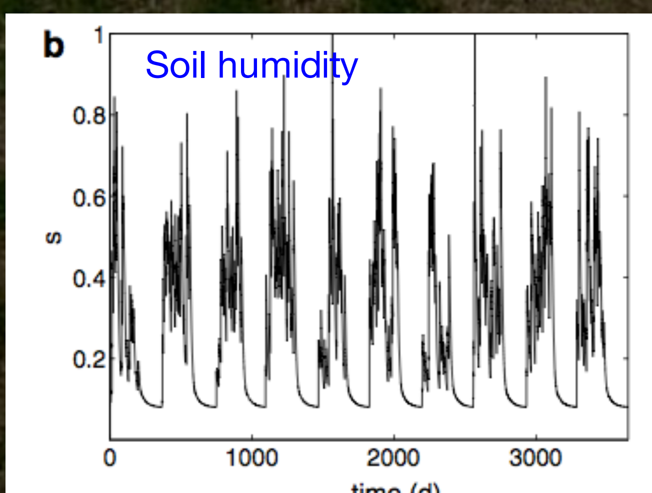
Ref: Ruel, J.J., Ayres, M.P., 1999 *Trends Ecol. Evol.* 14, 361–366.

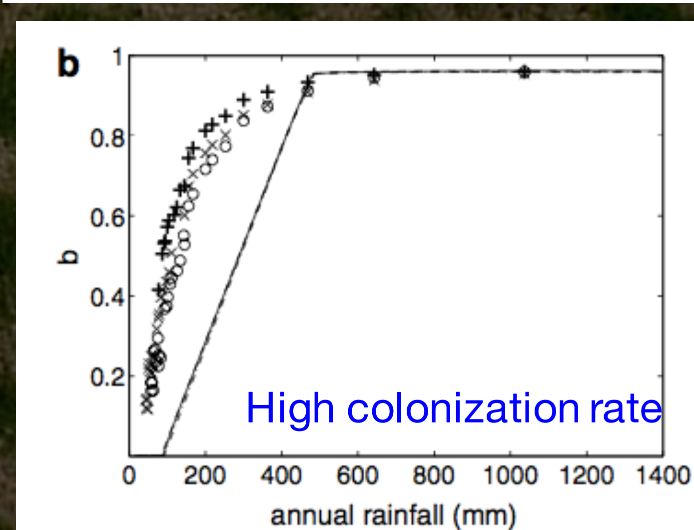
Vegetation persistence in a simple ecohydrological model

(With an active dry season)



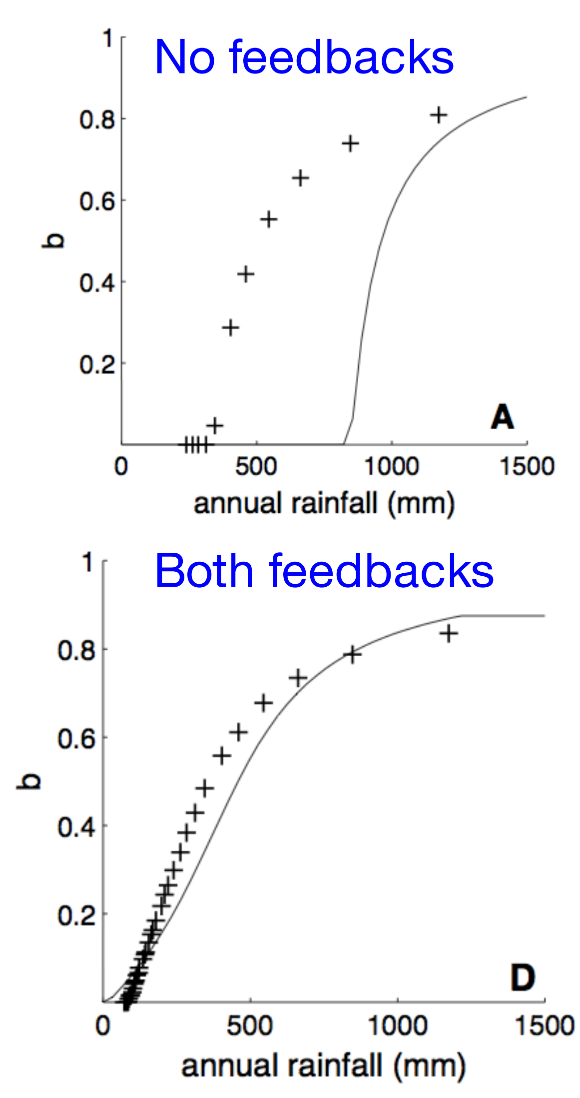






Role of vegetation feedbacks

An extension of the previous ecohydrological model to two soil layers and distinguishing bare and vegetated soils (Baudena et al. 2008)



Two feedbacks were considered:

- reduced evaporation due to shading
- increased infiltration in vegetated areas

Ref: Baudena and Provenzale Hydrol. Earth Syst. Sci., 12, 679–689, 2008

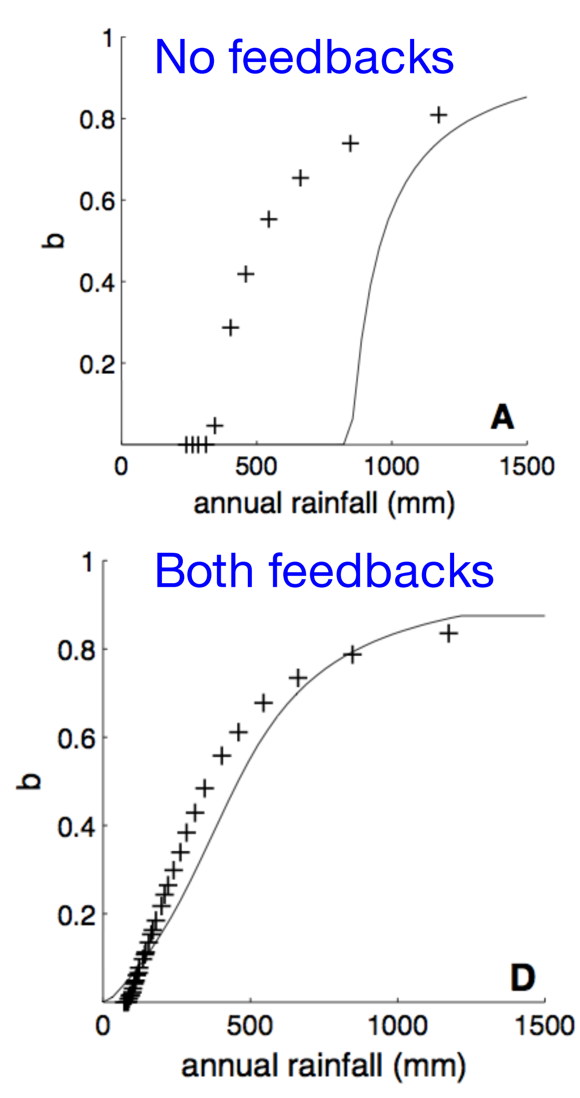
Role of vegetation feedbacks

An extension of the previous ecohydrological model to two soil layers and distinguishing bare and vegetated soils (Baudena et al. 2008)

Two feedbacks were considered:

- reduced evaporation due to shading
- increased infiltration in vegetated areas

The influence of vegetation feedbacks is larger when rainfall is kept constant in time

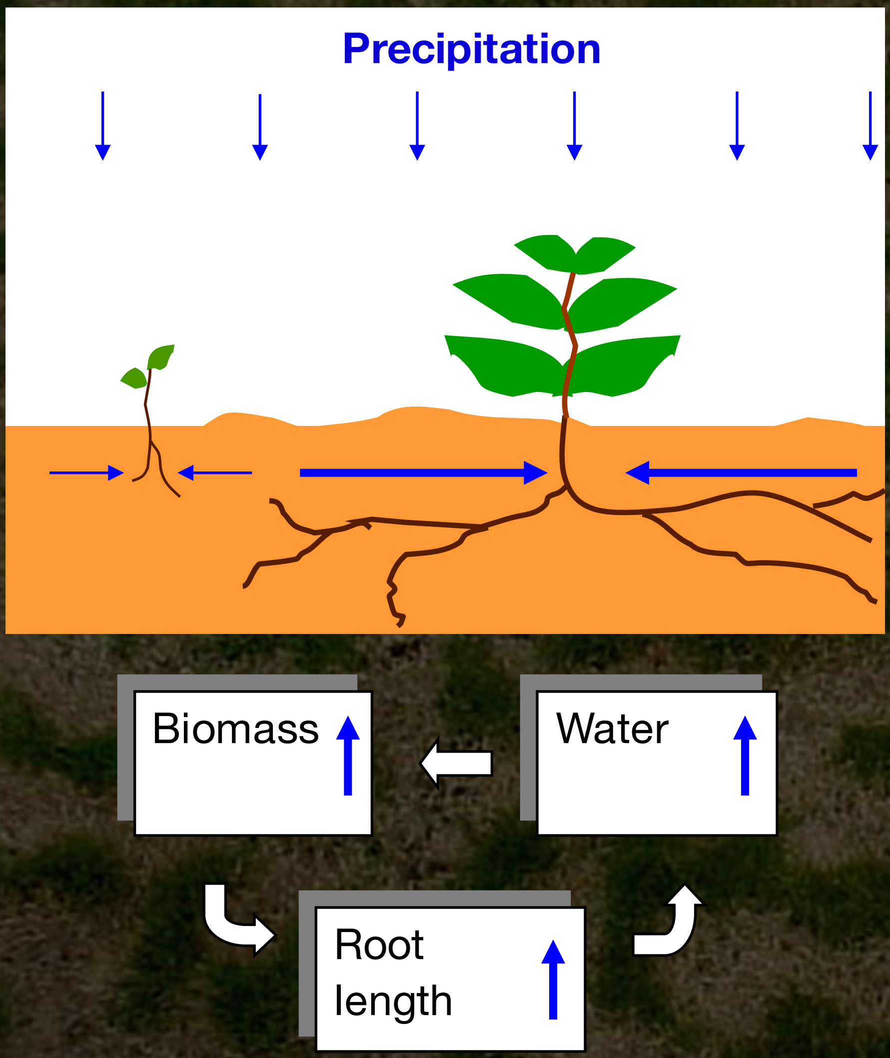


Ref: Baudena and Provenzale Hydrol. Earth Syst. Sci., 12, 679–689, 2008

Dryland vegetation – Local feedback Mechanisms

Root uptake feedback

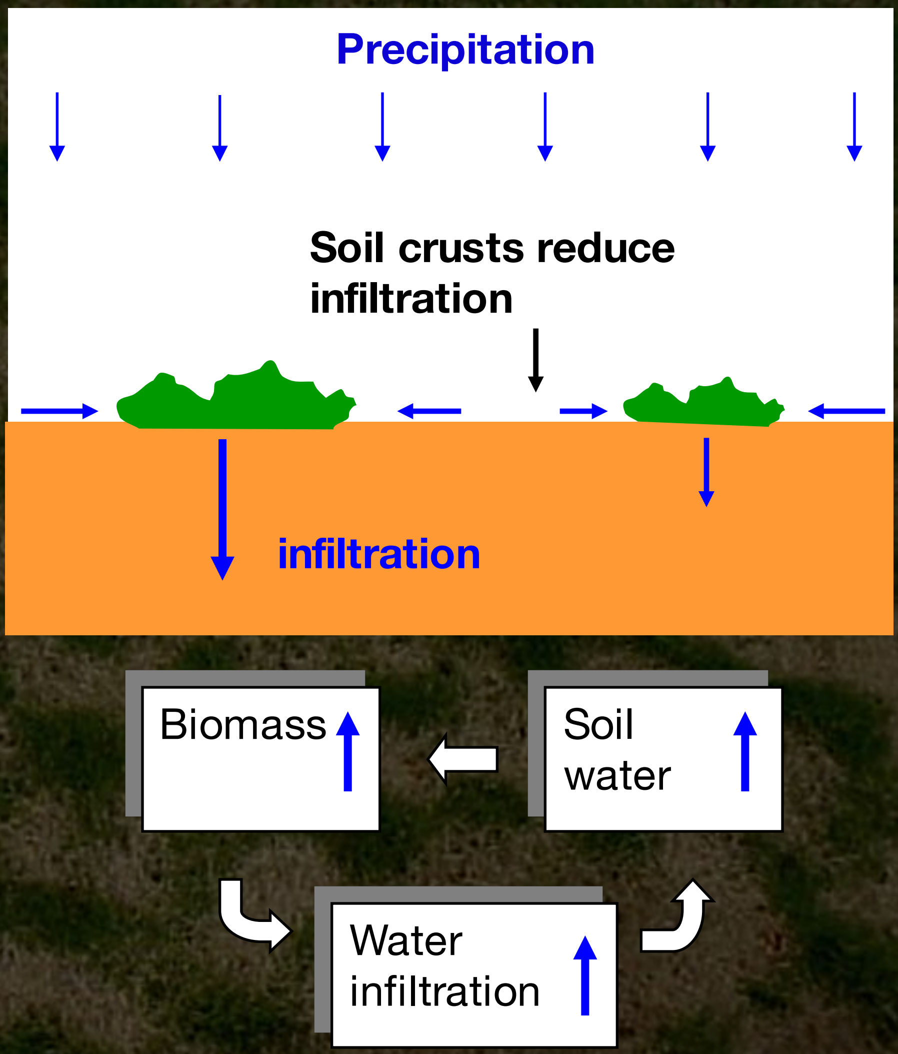
Long range competition



Infiltration feedback

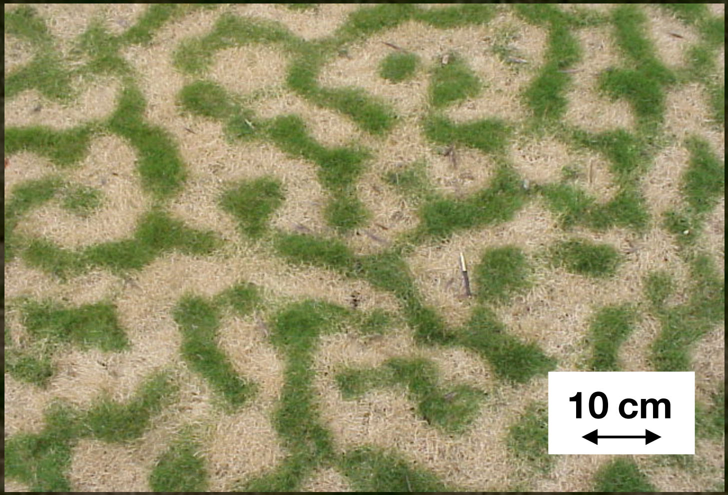
Local facilitation +

Long range competition



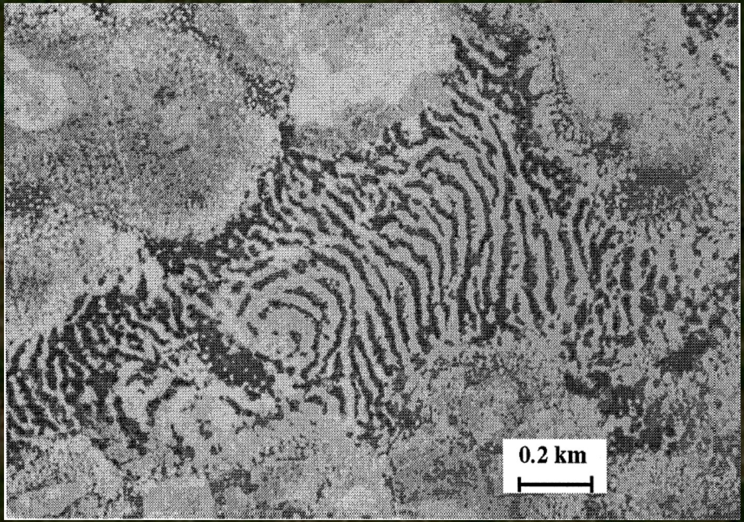
Vegetation patterns in drylands

Paspalum vaginatum, Negev



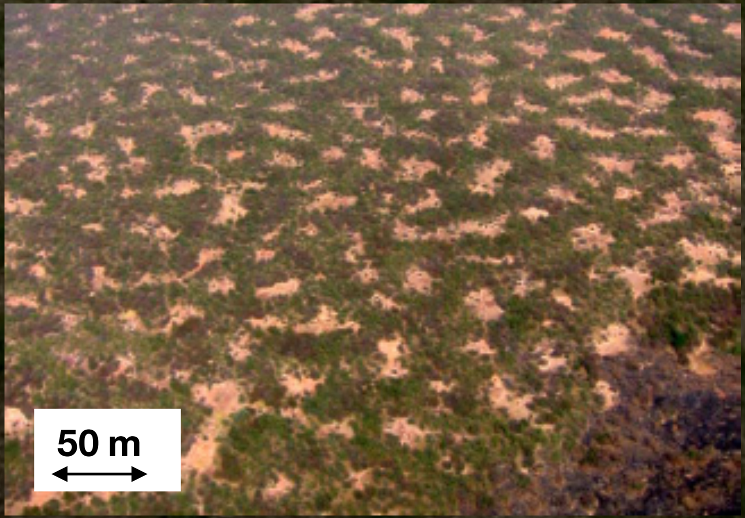
Hardenberg, Meron, Shachak, Zarmi, PRL (2001)

Vegetation bands ("Tiger Bush")



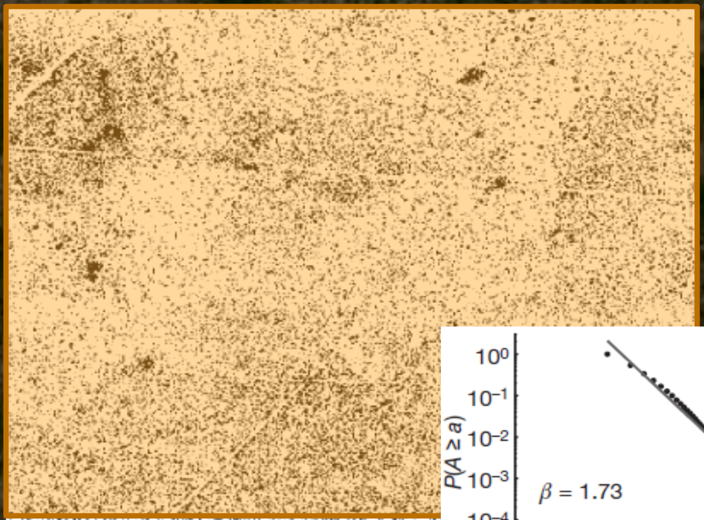
Valentin et al., *Catena* **37**, *1-24* (1999)

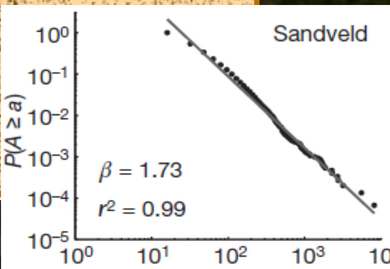
Shrubs and grasses in SW Niger



Barbier et al. Journal of Ecology (2006)

Wide patch size distributions





Scanlon et al.,
Nature **449**, (2007)

A spatially extended model

Plant biomass density	$B(\mathbf{x},t)$	[Kg/m^2]
Soil moisture	$w(\mathbf{x},t)$	[Kg/m^2]
Surface water height	$H(\mathbf{x},t)$	[mm]

$$\frac{\partial b}{\partial t} = \text{Growth} - \text{Mortality} + \text{Dispersion}$$

$$\frac{\partial h}{\partial t} = \text{Precipitation} - \text{Infiltration} + \text{Diffusion}$$

$$\frac{\partial w}{\partial t} = \text{Infiltration} - \text{Evaporation} - \text{Root uptake} + \text{Diffusion}$$

Soil water *w*

Biomass *b*

Feedbacks

Refs: Gilad *et al.*, *PRL* **93** 2004;
Gilad *et al. JTB, 2007*

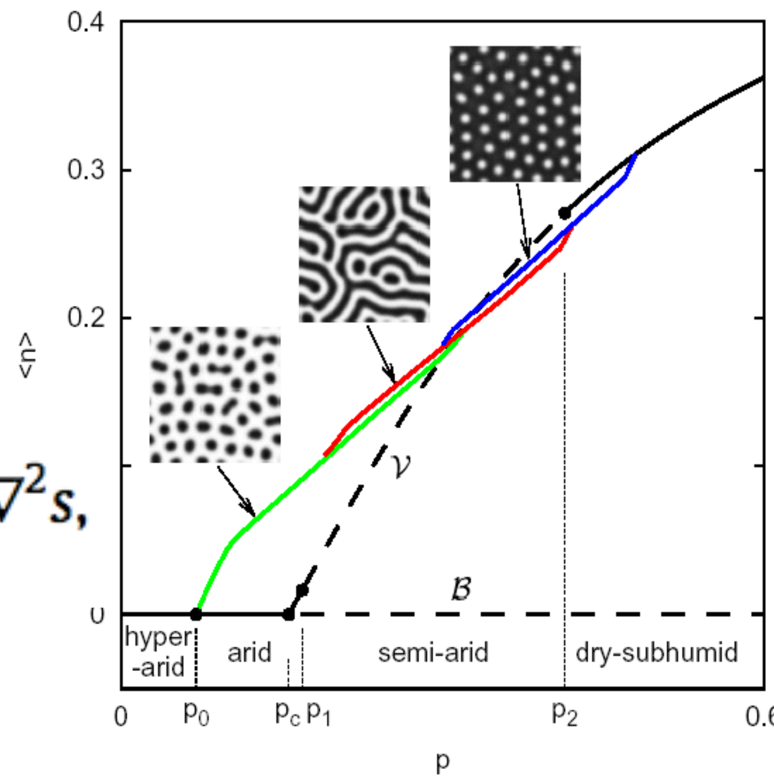
A spatially extended model

Plant biomass density $B(\mathbf{x},t)$ [Kg/m^2]
Soil moisture $s(\mathbf{x},t) = w(x,t)/w_{MAX}$
Surface water height $H(\mathbf{x},t)$ [mm]

$$\frac{\partial B}{\partial t} = G_B[s]B\left(1 - \frac{B}{K}\right) - MB + D_B \nabla^2 B,$$

$$\frac{\partial s}{\partial t} = \frac{IH}{W_{MAX}} - \frac{Ns}{1 + RB/K} - G_s[B]\mathscr{F}(s) + D_W \nabla^2 s,$$

$$\frac{\partial H}{\partial t} = P - IH + D_H \nabla^2 (H^2),$$



Root uptake:

$$G_B[s] = \Lambda_{MAX} \int G(\mathbf{x},\mathbf{x}',t)\mathscr{F}(s(\mathbf{x}',t))\,\mathrm{d}\mathbf{x}',$$

$$G(\mathbf{x},\mathbf{x}',t) = \frac{1}{2\pi S_0}\exp\left[-\frac{|\mathbf{x}-\mathbf{x}'|^2}{2[S_0(1+EB(\mathbf{x},t))]^2}\right]$$

$$G_s[B] = \Gamma \int G(\mathbf{x}',\mathbf{x},t)B(\mathbf{x}',t)\,\mathrm{d}\mathbf{x}',$$

Infiltration:

$$I = \alpha \frac{b + qf}{b + q}$$

A spatially extended model

Plant biomass density $B(\mathbf{x},t)$ [Kg/m^2]
Soil moisture $s(\mathbf{x},t) = w(x,t)/w_{MAX}$
Surface water height $H(\mathbf{x},t)$ [mm]

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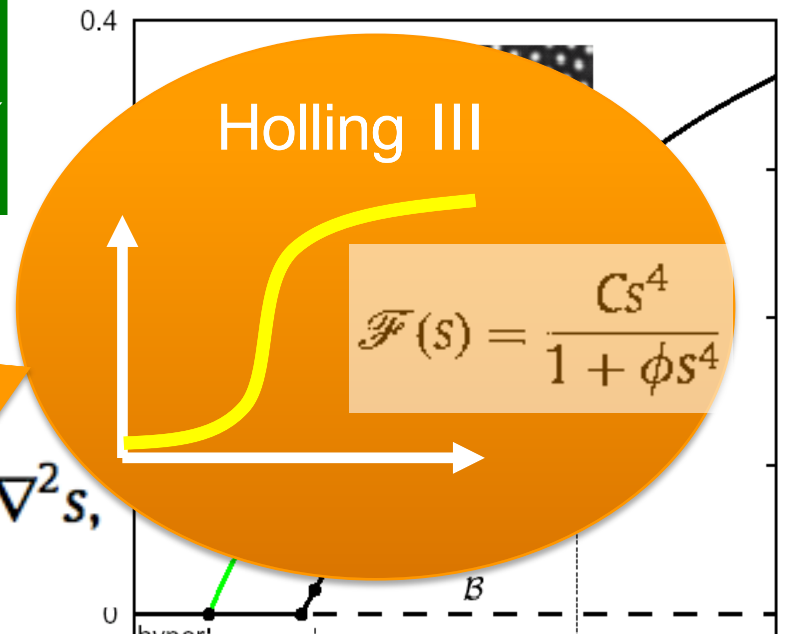
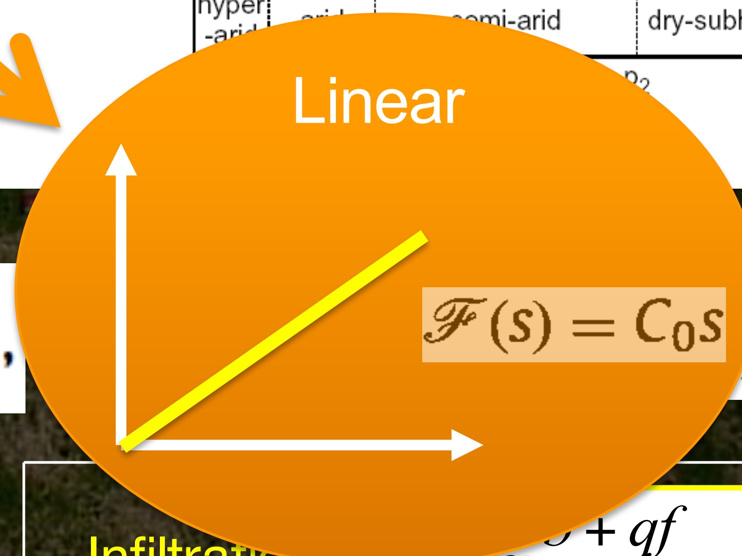
$$\frac{\partial s}{\partial t} = \frac{IH}{W_{MAX}} - \frac{Ns}{1 + RB/K} - G_s[B]\mathscr{F}(s) + D_W \nabla^2 s,$$

$$\frac{\partial H}{\partial t} = P - IH + D_H \nabla^2 (H^2),$$



$$\mathscr{F}(s) = \frac{Cs^4}{1 + \phi s^4}$$



$$\mathscr{F}(s) = C_0 s$$

Root uptake:

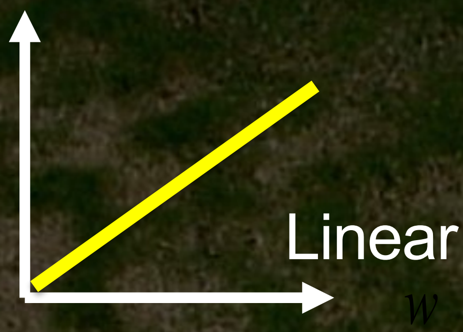
$$G_B[s] = \Lambda_{MAX} \int G(\mathbf{x}, \mathbf{x}', t)\mathscr{F}(s(\mathbf{x}', t))\, d\mathbf{x}',$$

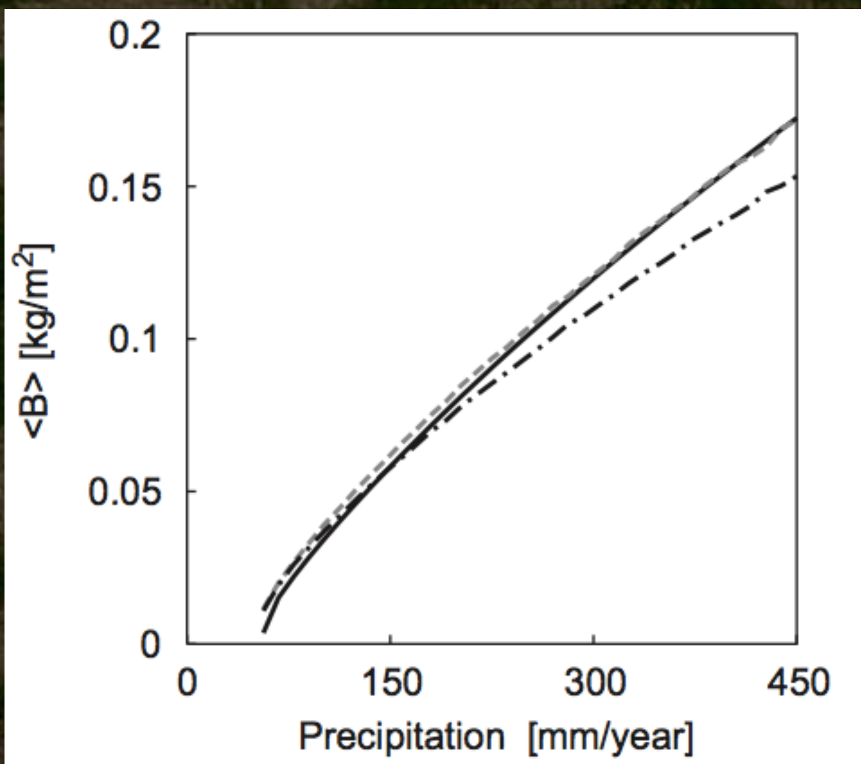
$$G_s[B] = \Gamma \int G(\mathbf{x}', \mathbf{x}, t)B(\mathbf{x}', t)\, d\mathbf{x}',$$

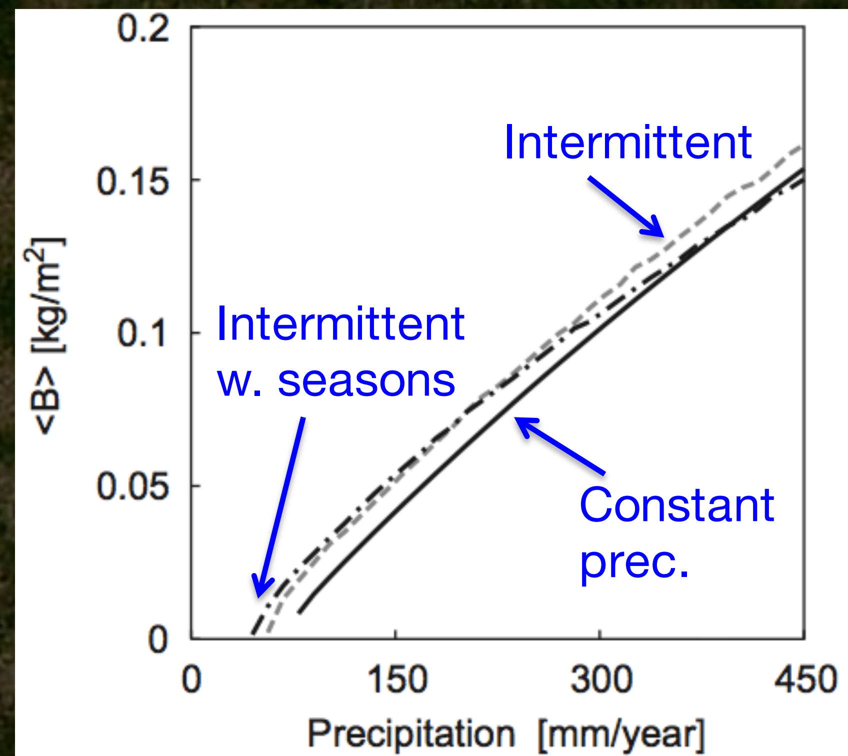
Infiltration:

$$I = \alpha \frac{\ldots + qf}{b + q}$$

Impact of the water uptake functional form

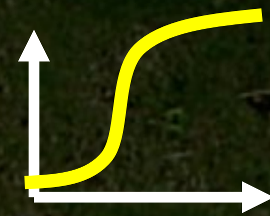




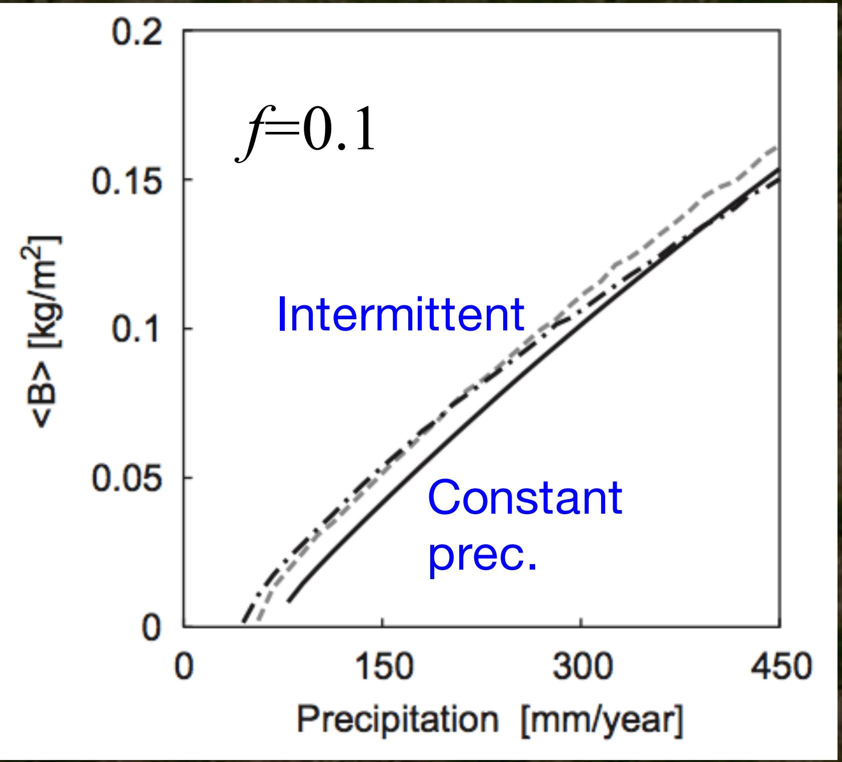


Ref: Kletter et al. *Journal of Theoretical Biology* 256 (2009) 574–583

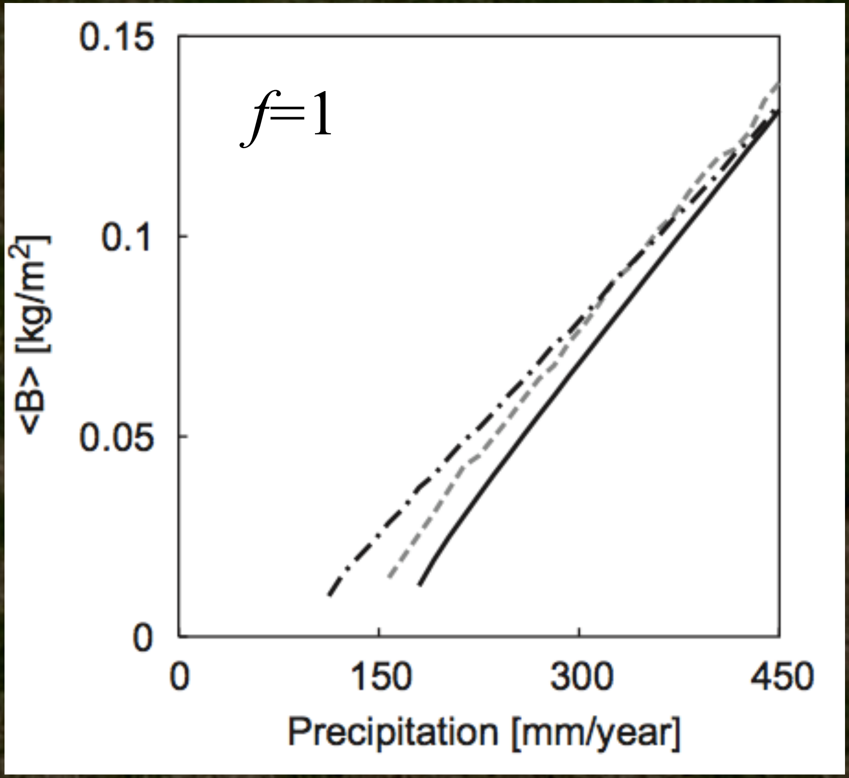
Impact of the infiltration feedback



With infiltration feedback



No infiltration feedback



Ref: Kletter et al. *Journal of Theoretical Biology* 256 (2009) 574–583

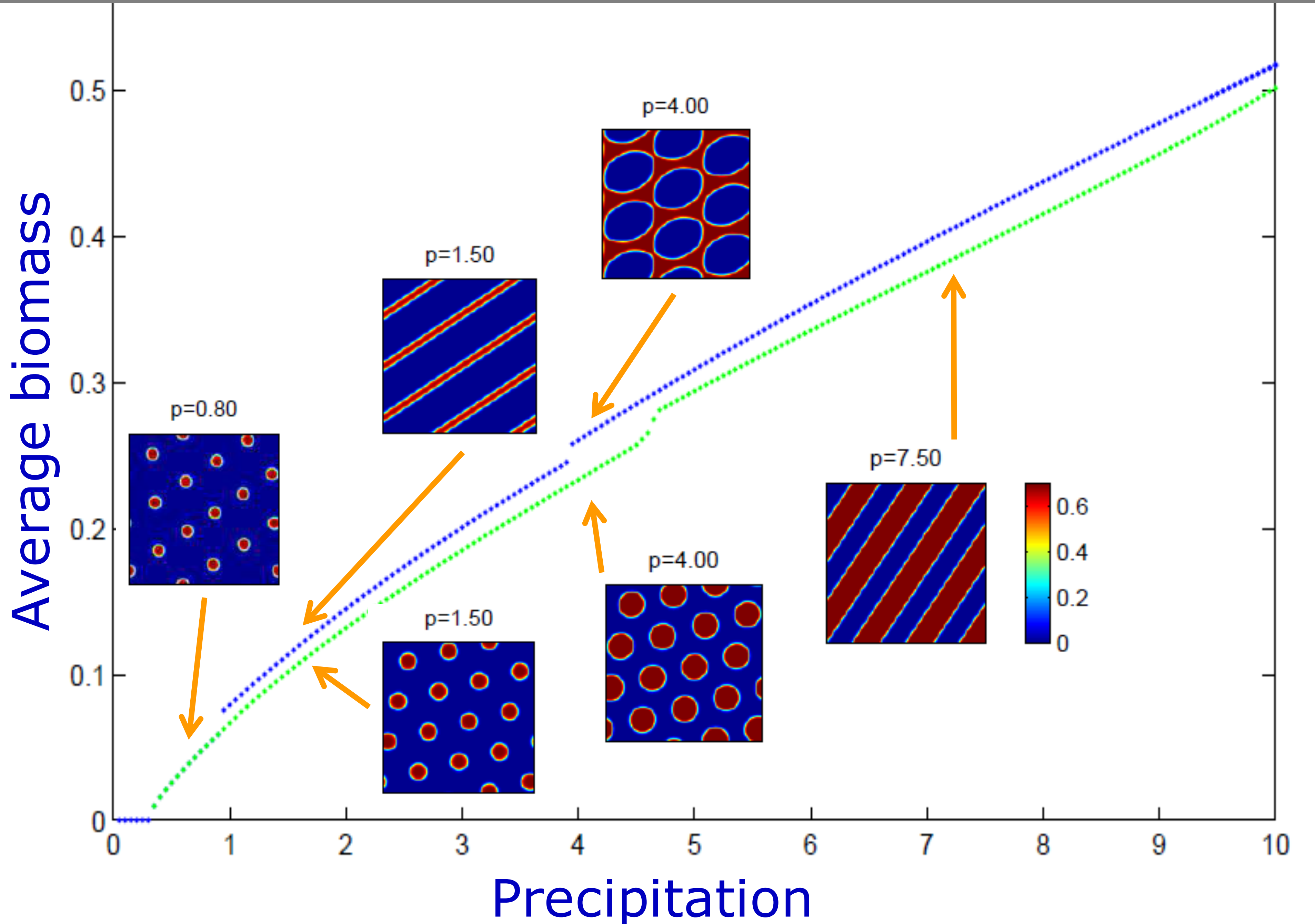
In the presence of intermittent rainfall

the effect of a concave-up water uptake form is stronger in the absence of significant vegetation feedbacks

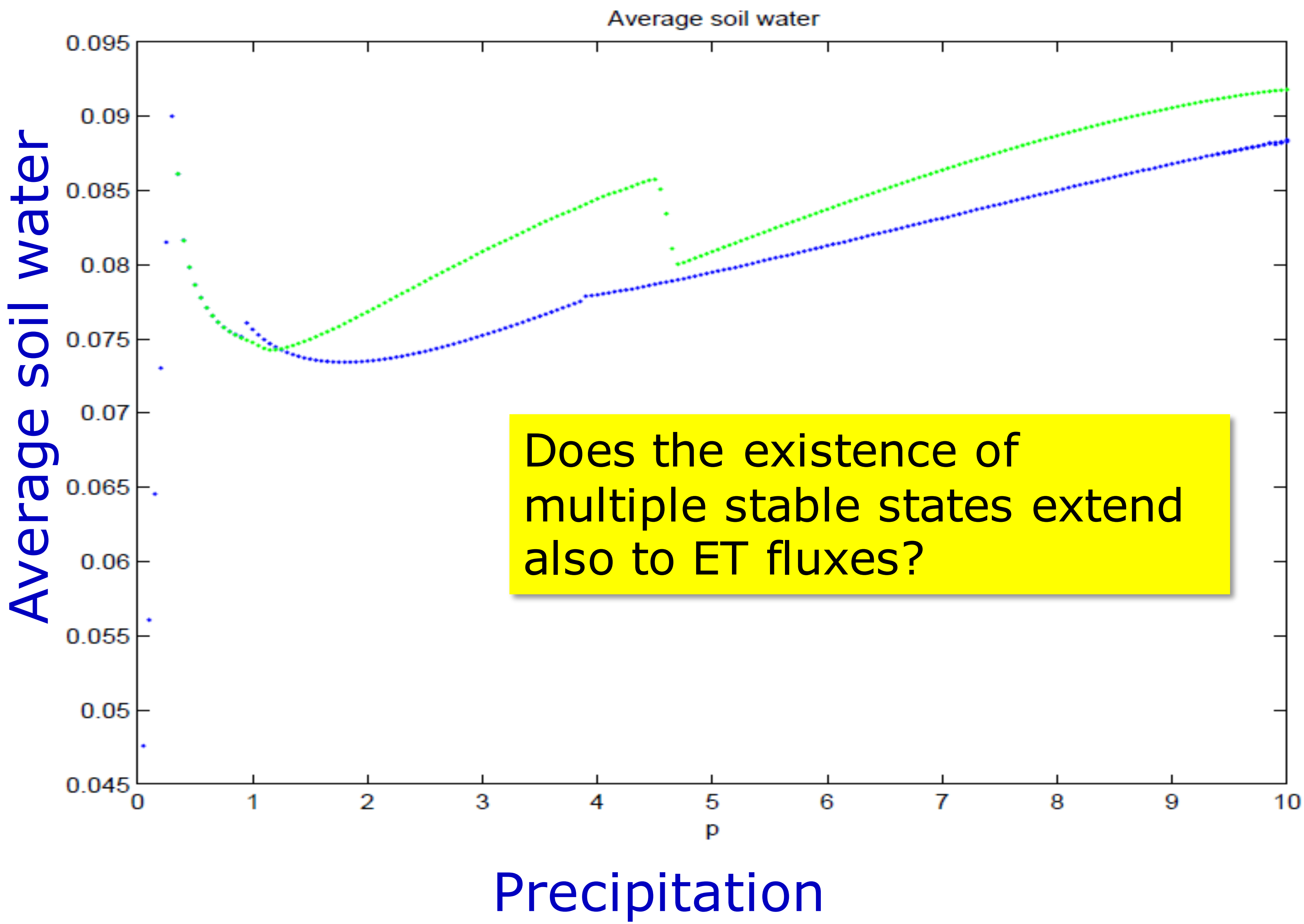
So, dryland vegetation has two (possibly alternative) strategies for enhancing its survival:

- be able to use the infiltration feedback
- evolve a concave-up form of the dependence of the intensity of the water uptake on soil moisture

Multiple stable states of patterned vegetation

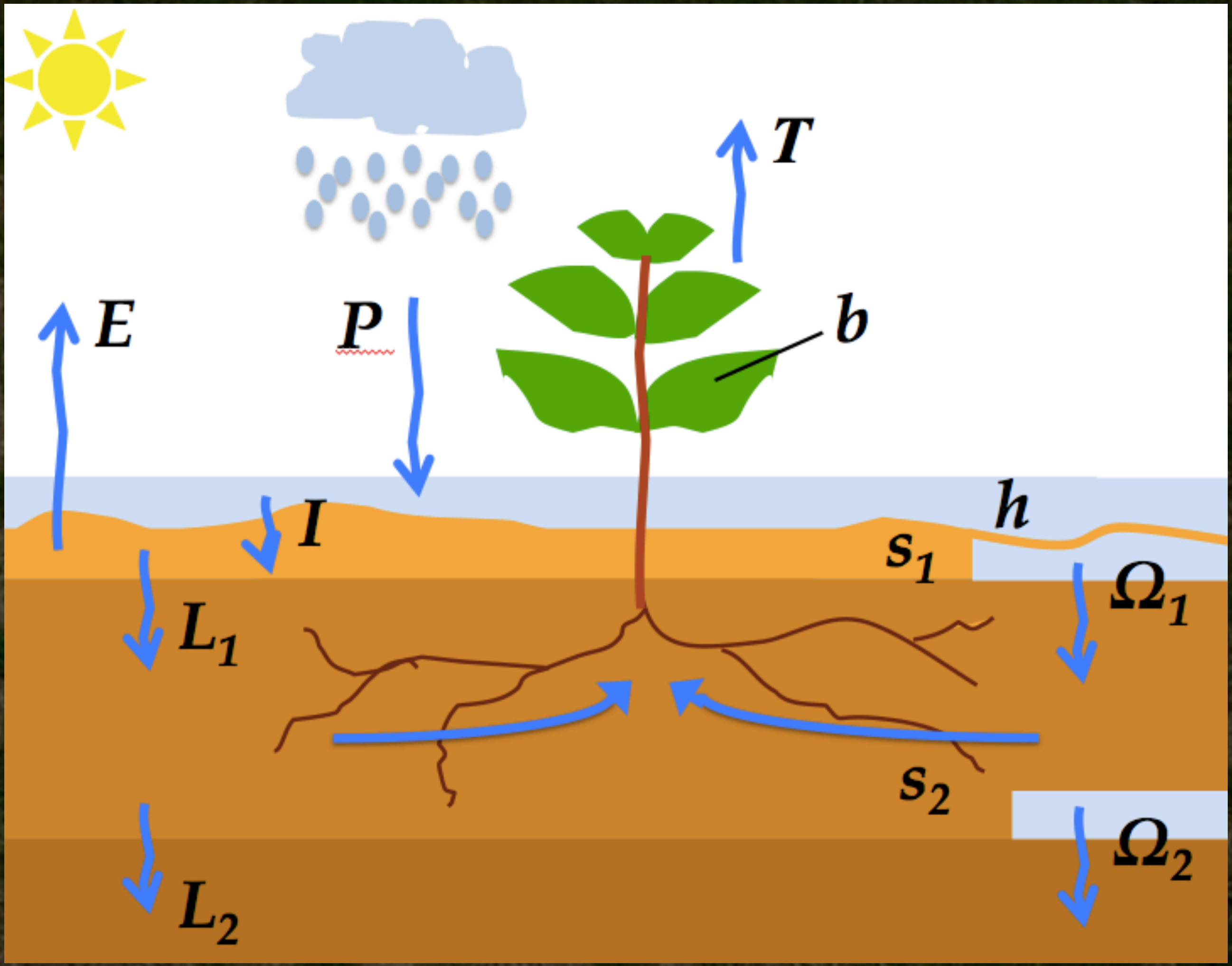


Multiple stable states



Does the existence of multiple stable states extend also to ET fluxes?

A two layer Model for Soil water-Vegetation Interactions

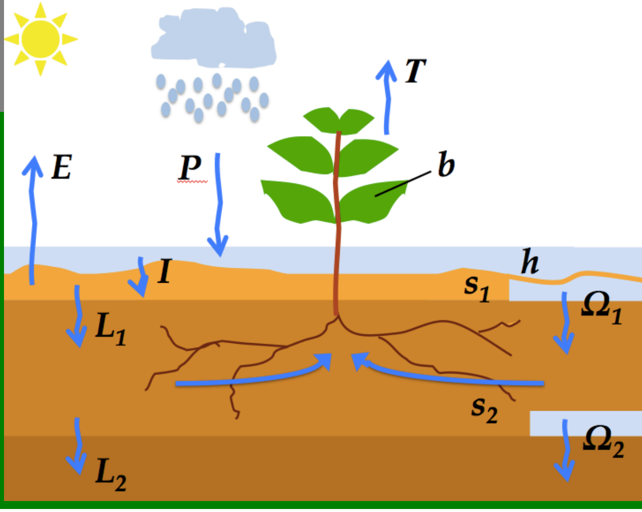


Adapted for:

- Intermittent precipitation
- Rapid Evaporation typically only from the top soil layer (5-10 cm)

A two layer Model

Plant biomass density	$B(\mathbf{x},t)$	[Kg/m^2]
Surface water height	$H(\mathbf{x},t)$	[mm]
Rel. soil moisture layer 1	$s_1(\mathbf{x},t)$	[Kg/m^2]
Rel. soil moisture layer 2	$s_1(\mathbf{x},t)$	[Kg/m^2]



$$\frac{\partial b}{\partial t} = \text{Growth} - \text{Mortality} + \text{Dispersion}$$

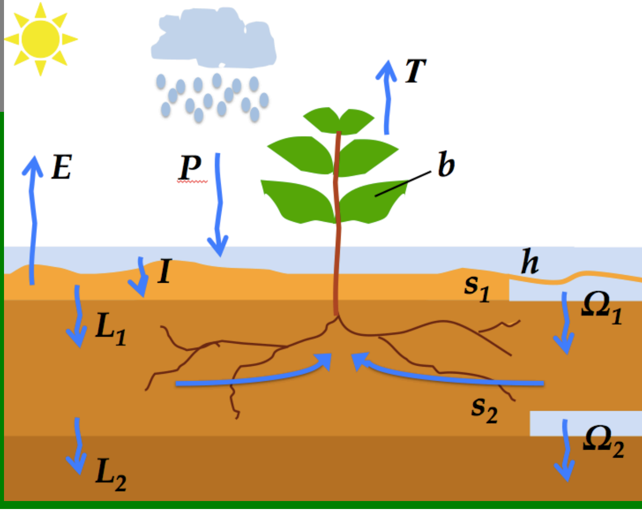
$$\frac{\partial h}{\partial t} = \text{Precipitation} - \text{Infiltration} + \text{Runoff}$$

$$\frac{\partial s_1}{\partial t} = \text{Infiltration} - \text{Evaporation} - \text{Infiltration/ Leakage to 2} + \text{Diffusion}$$

$$\frac{\partial s_2}{\partial t} = \text{Infiltration/leakage from 1} - \text{Leakage to deep} - \text{Root uptake} + \text{Diffusion}$$

A two layer Model

Plant biomass density	$B(\mathbf{x},t)$	[Kg/m^2]
Surface water height	$H(\mathbf{x},t)$	[mm]
Rel. soil moisture layer 1	$s_1(\mathbf{x},t)$	[Kg/m^2]
Rel. soil moisture layer 2	$s_1(\mathbf{x},t)$	[Kg/m^2]



$$\frac{\partial b}{\partial t} = \lambda G_b[s_2]b\left(1 - \frac{b}{K}\right) - Mb + D_b\nabla^2 b$$

$$\frac{\partial h}{\partial t} = P - I[b]h + D_h\nabla^2(h^2)$$

$$nZ_1\frac{\partial s_1}{\partial t} = I[b]h - E[s_1, b] - L_k[s_1] + nZ_1 D_s\nabla^2 s_1 - \Omega[s_1]$$

$$nZ_2\frac{\partial s_2}{\partial t} = \Omega[s_1] + L_k[s_1] - T[s_2, b] - L_k[s_2] + nZ_2 D_s\nabla^2 s_2 - \Omega[s_2]$$

A two-layer model

$$\frac{\partial b}{\partial t} = \lambda G_b[s_2]\, b\left(1 - \frac{b}{K}\right) - Mb + D_b \nabla^2 b$$

$$\frac{\partial h}{\partial t} = P - I[b]h + D_h \nabla^2 (h^2)$$

$$nZ_1 \frac{\partial s_1}{\partial t} = I[b]h - E[s_1, b] - L_k[s_1] + nZ_1 D_s \nabla^2 s_1 - \Omega[s_1] = F_{s_1} - \Omega[s_1]$$

$$nZ_2 \frac{\partial s_2}{\partial t} = \Omega[s_1] + L_k[s_1] - T[s_2, b] - L_k[s_2] + nZ_2 D_s \nabla^2 s_2 - \Omega[s_2] = F_{s_2} - \Omega[s_2]$$

Growth rate: $G_b[s_2] = \int G(\mathbf{x}, \mathbf{x}', t) s_2(\mathbf{x}', t)\, d\mathbf{x}'$

Evaporation: $E[s_1, b] = \frac{nZ_1 \nu}{1 + \rho b/K} s_1$

Uptake/transpiration: $T[s_2, b] = nZ_2 \gamma \int G(\mathbf{x}', \mathbf{x}, t)\, b(\mathbf{x}')\, d\mathbf{x}'$

Leakage: $L_k[s_i] = K_s s_i^c$

$$G(\mathbf{x}, \mathbf{x}', t) = \frac{1}{2\pi S_0} \exp\left[-\frac{|\mathbf{x} - \mathbf{x}'|^2}{2[S_0(1 + \eta b(\mathbf{x}, t))]^2}\right]$$

Infiltration: $I = \alpha \frac{b + qf}{b + q}$

(Modification of Gilad *et al. JTB, 2007*)

When a soil layer saturates excess water is assumed to infiltrate immediately to deeper layer

$$\Omega[s_i] = \begin{cases} F_{s_i} - nZ_i \frac{1 - s_i}{\Delta t} & \text{if} \quad F_{s_i} > nZ_i \frac{1 - s_i}{\Delta t} \\ 0 & \text{otherwise} \end{cases}$$

A two-layer model

$$\frac{\partial b}{\partial t} = \lambda G_b[s_2] b \left(1 - \frac{b}{K}\right) - Mb + D_b \nabla^2 b$$

$$\frac{\partial h}{\partial t} = P - I[b]h + D_h \nabla^2 (h^2) \longrightarrow Ih - D_h \nabla^2 \left(h^2\right) = P.$$

$$nZ_1 \frac{\partial s_1}{\partial t} = I[b]h - E[s_1, b] - L_k[s_1] + nZ_1 D_s \nabla^2 s_1 - \Omega[s_1] = F_{s_1} - \Omega[s_1]$$

$$nZ_2 \frac{\partial s_2}{\partial t} = \Omega[s_1] + L_k[s_1] - T[s_2, b] - L_k[s_2] + nZ_2 D_s \nabla^2 s_2 - \Omega[s_2] = F_{s_2} - \Omega[s_2]$$

Growth rate: $G_b[s_2] = \int G(\mathbf{x}, \mathbf{x}', t) s_2(\mathbf{x}', t) \mathrm{d}\mathbf{x}'$

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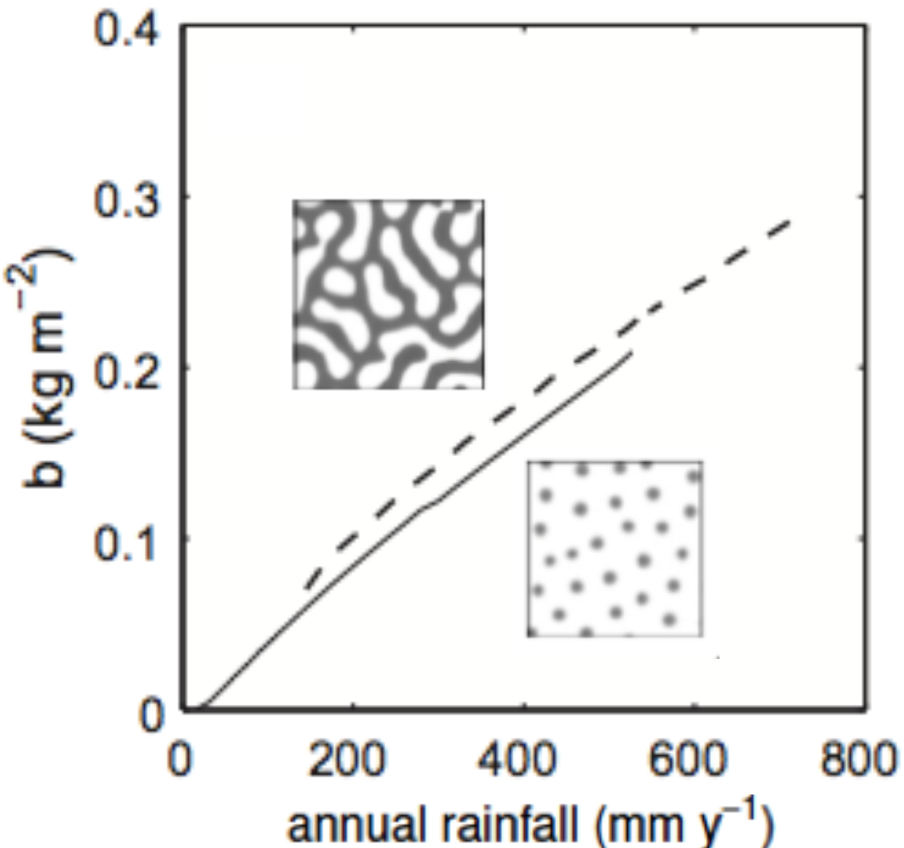
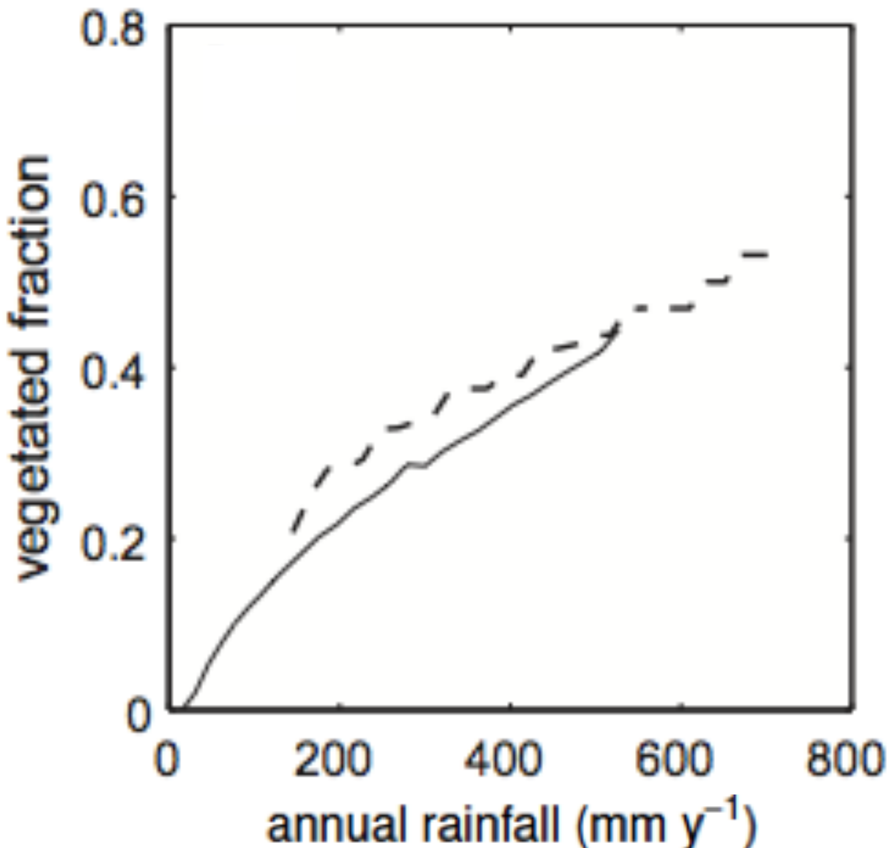
A two layer Model for Soil water-Vegetation Interactions

Using realistic (untuned) parameter values and with stochastic precipitation the model develops stable patterns in a wide range of average annual precipitations

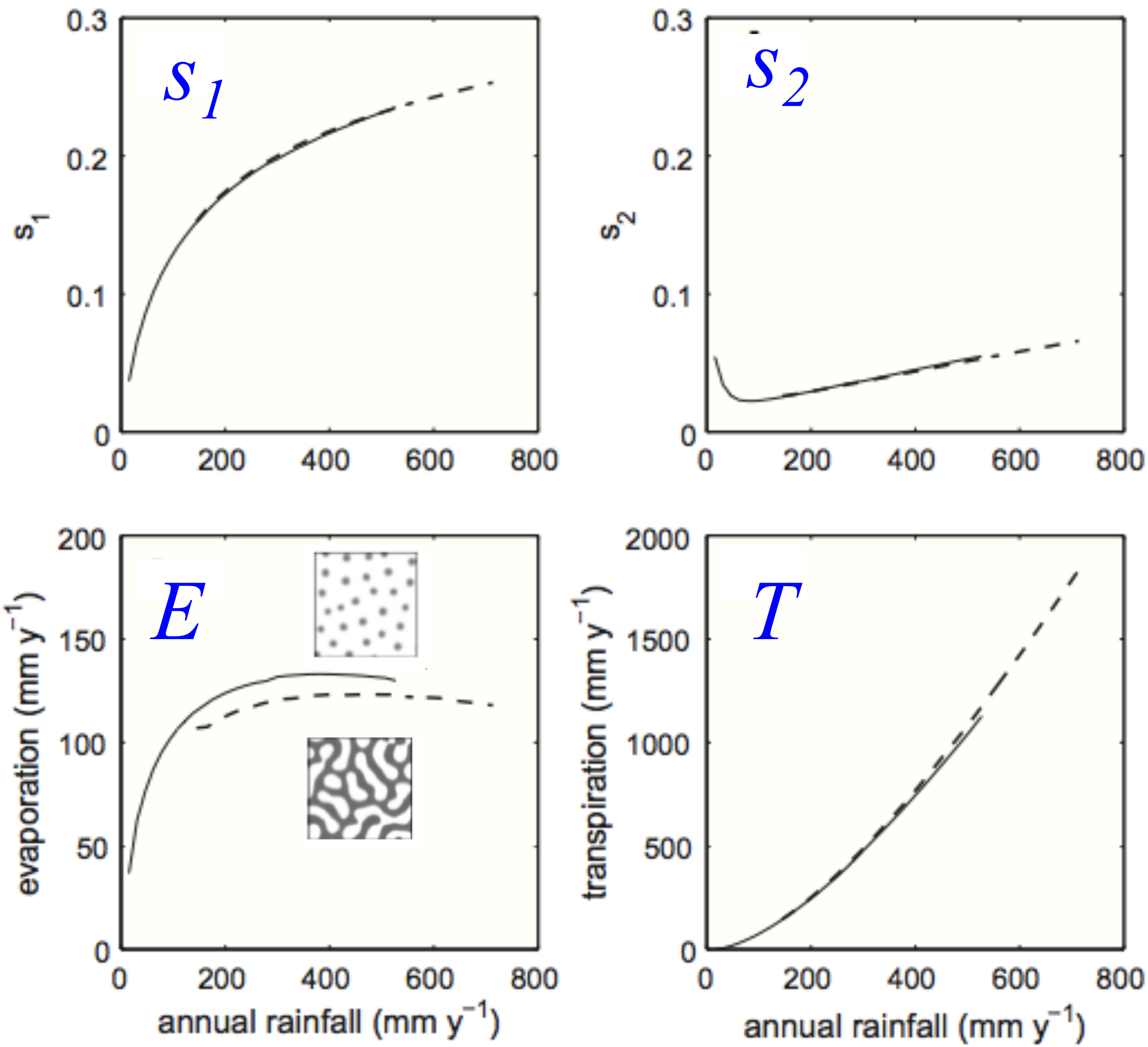
Biomass density



Vegetated fraction



Evapotranspiration fluxes and soil moisture after an event



Averaged over the 5 days following a precipitation event, over 100 yr of run (after 400 yr transient).

Vegetation patterns

- Comparison with HAPEX Sahel data (Galle et al. 2001) for a site with 228 mm/yr precip., banded vegetation

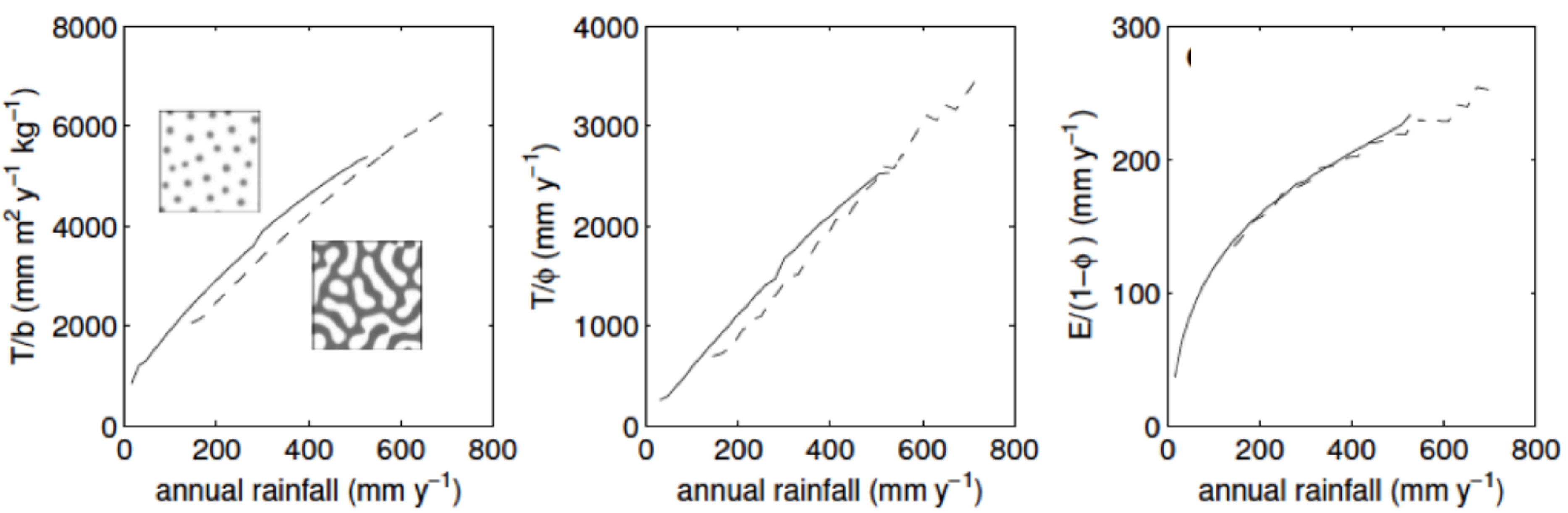
	Observed	Model
Cover	20%-25%	29%
Evapotranspiration from interbands	61%	54%
Evapotranspiration from bands	287%	210%

Dependence of evapotranspiration fluxes on pattern type

Transpiration flux per unit biomass density

Transpiration flux per unit vegetated area

Evaporation flux per unit bare soil



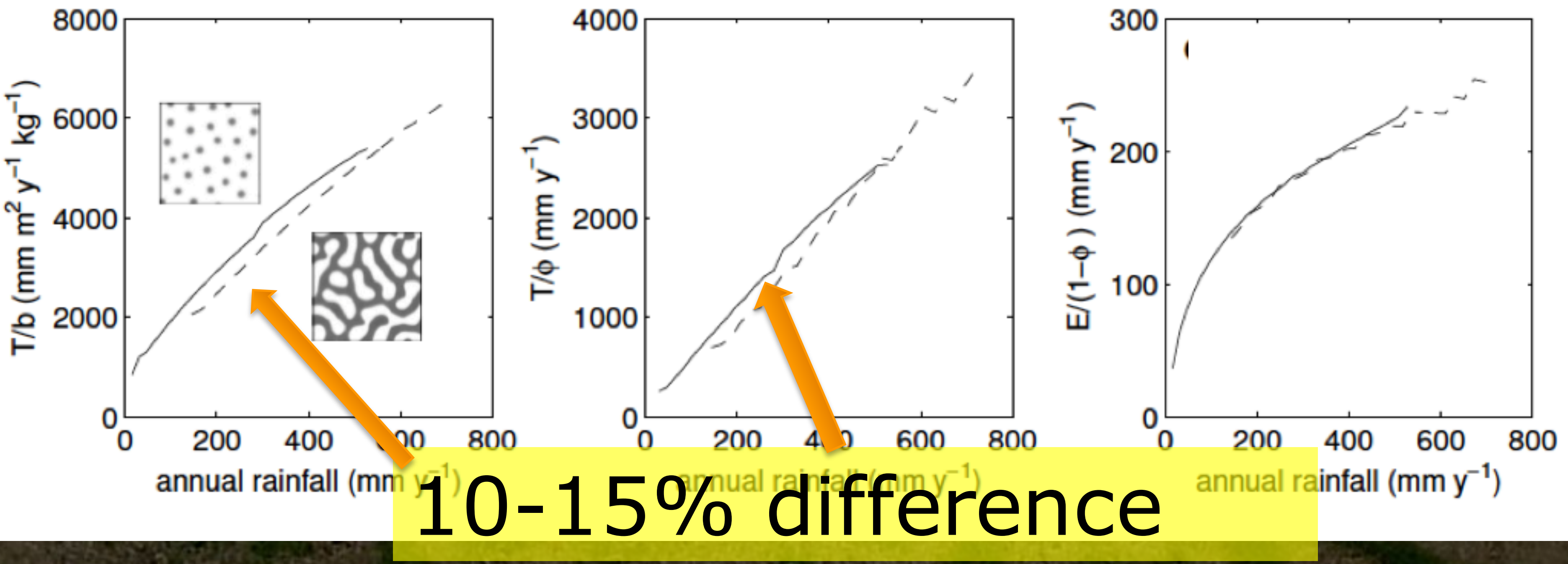
Averaged over the 5 days following a precipitation event and averaged over 100 yr of run (after 400 yr transient).

Dependence of evapotranspiration fluxes on pattern type

Transpiration flux per unit biomass density

Transpiration flux per unit vegetated area

Evaporation flux per unit bare soil



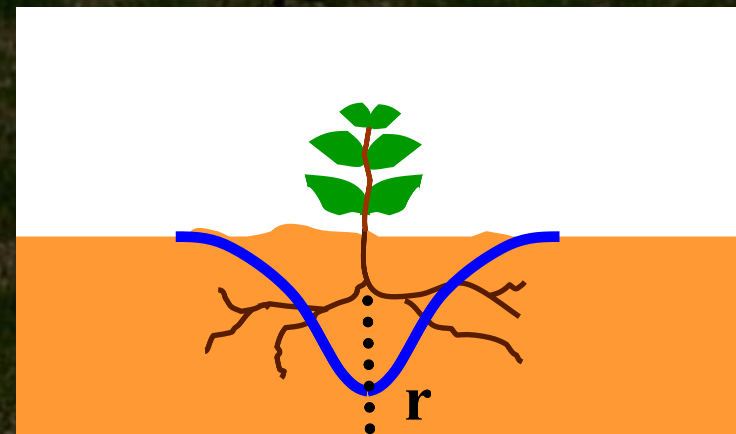
Averaged over the 5 days following a precipitation event and averaged over 100 yr of run (after 400 yr transient).

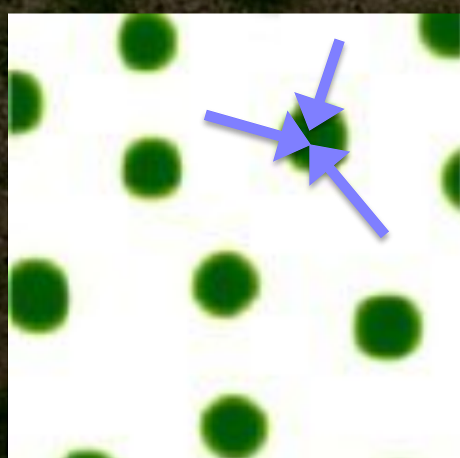
Pattern geometry plays a role

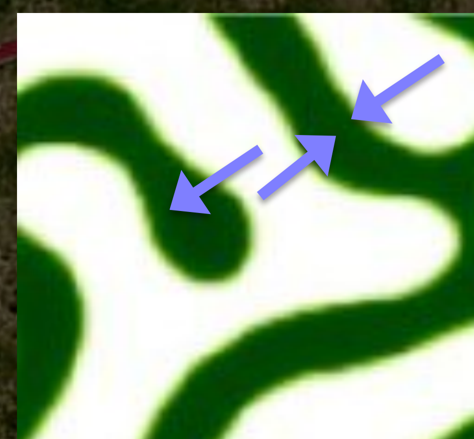
The role of pattern geometry

Higher transpiration per unit biomass for spots vs. bands

- Transpiration collects water through the roots also from surrounding area → less competition for spots vs bands



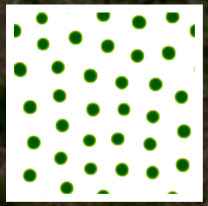




Natural vs. imposed patterns

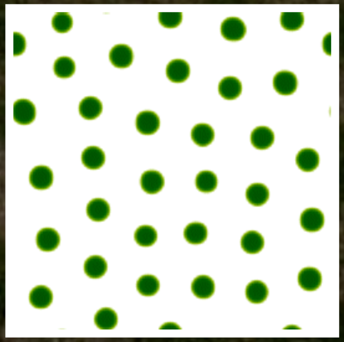
Differences between self-consistent patterns and imposed patterns ?

Pattern formed by model



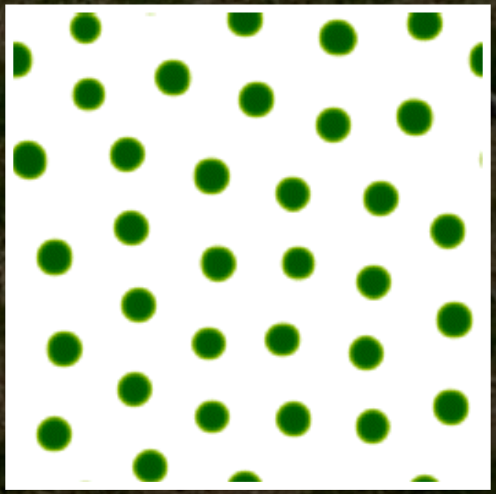
rescaled

L=2m



L=3.75m

rescaled



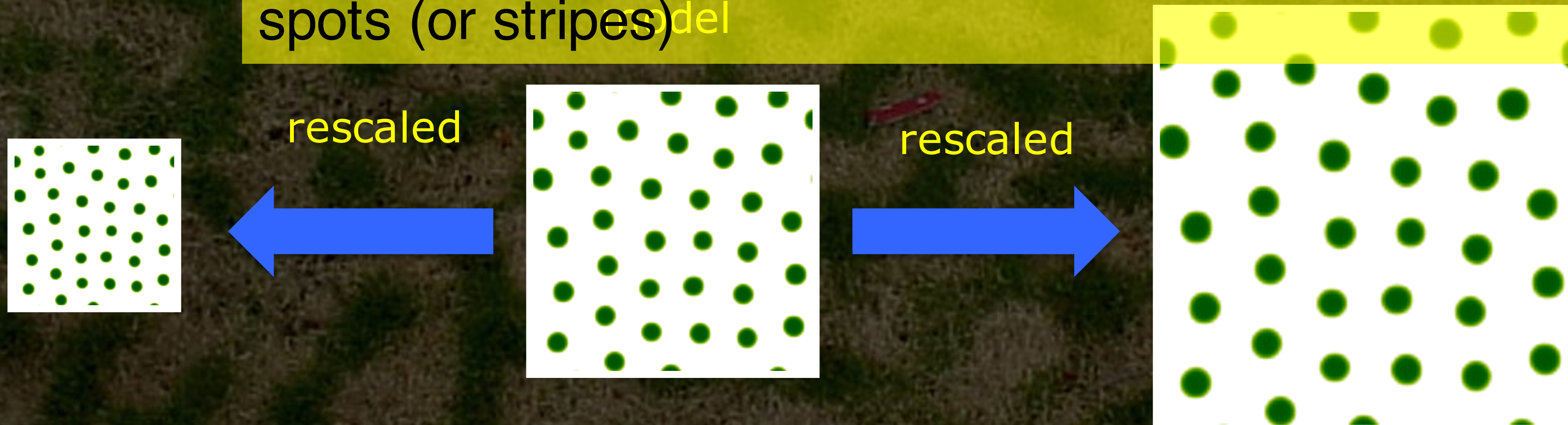
L=6m

Natural vs. imposed patterns

Differences between self-consistent patterns and imposed patterns ?

Same biomass density, fraction of space covered by vegetation, distribution of biomass inside a spot/stripe and same number and distribution of the spots (or stripes)

Pattern formed by model



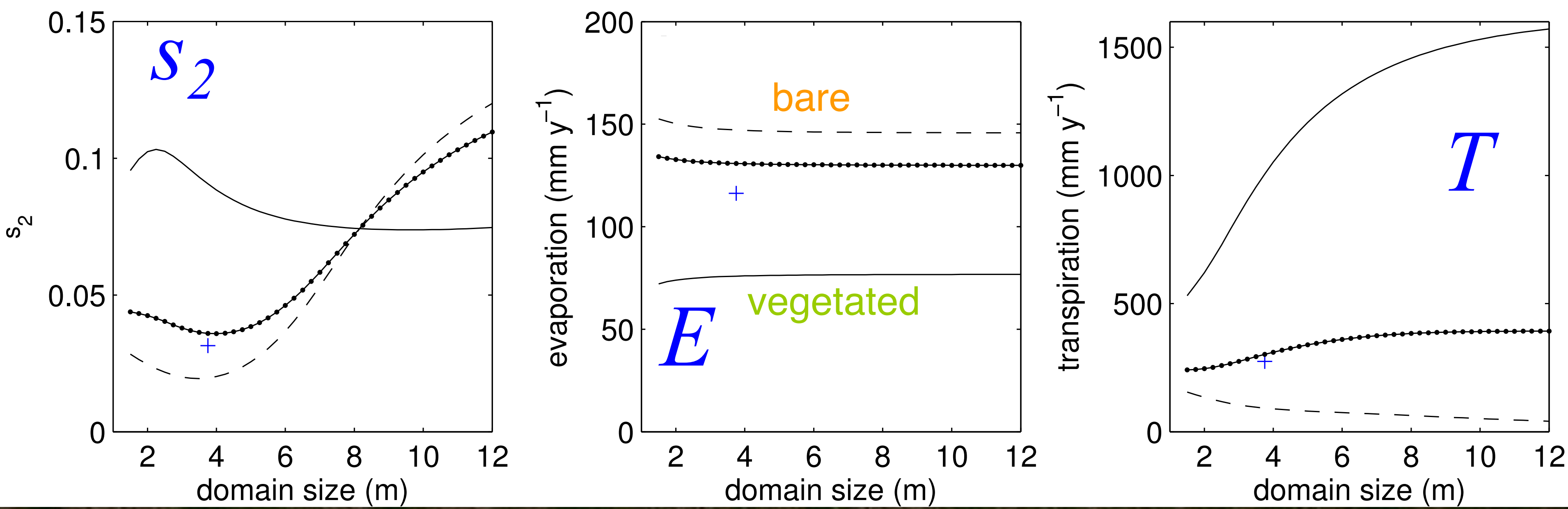
L=2m

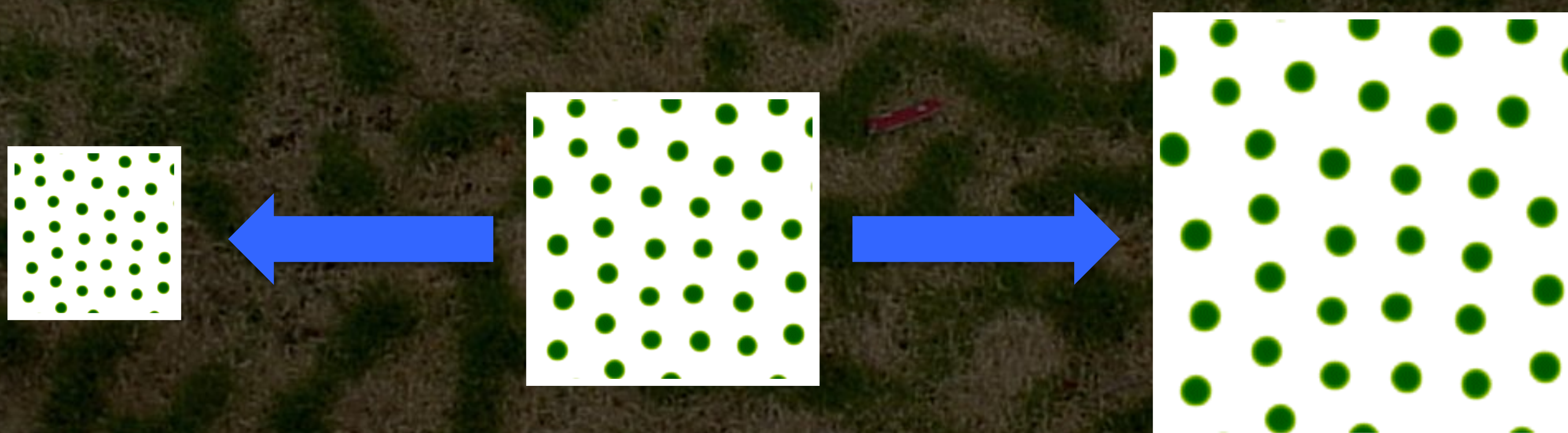
L=3.75m

L=6m

Natural vs. imposed patterns

$$\partial b/\partial t = 0$$





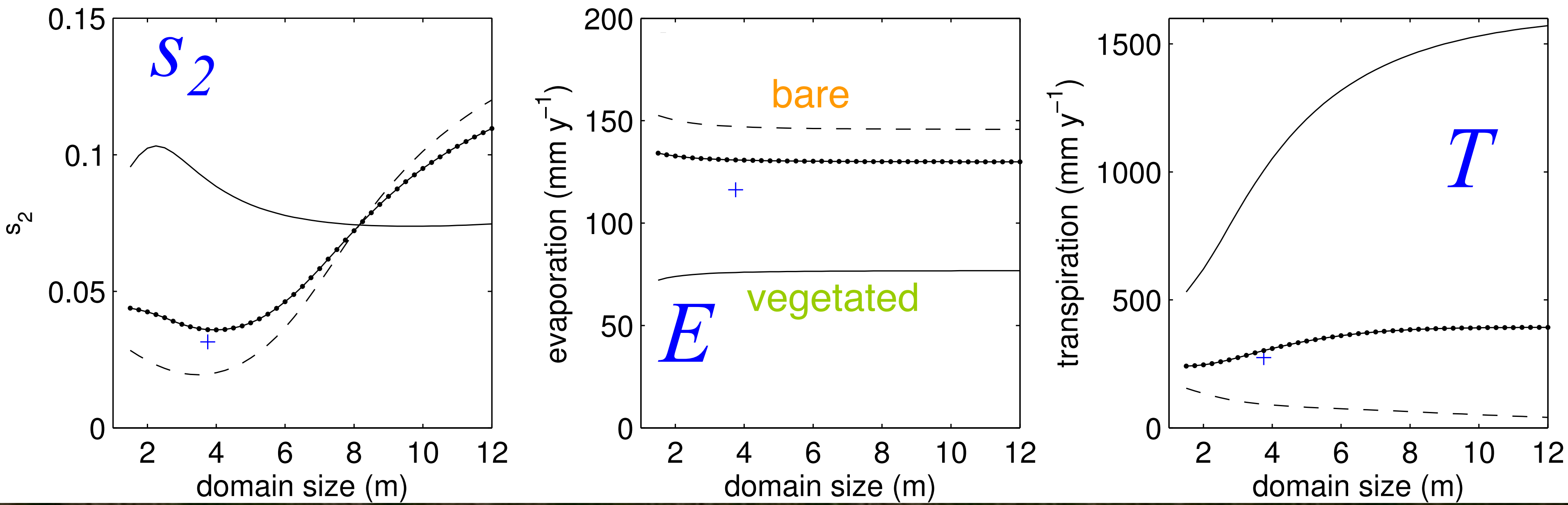
L=2m

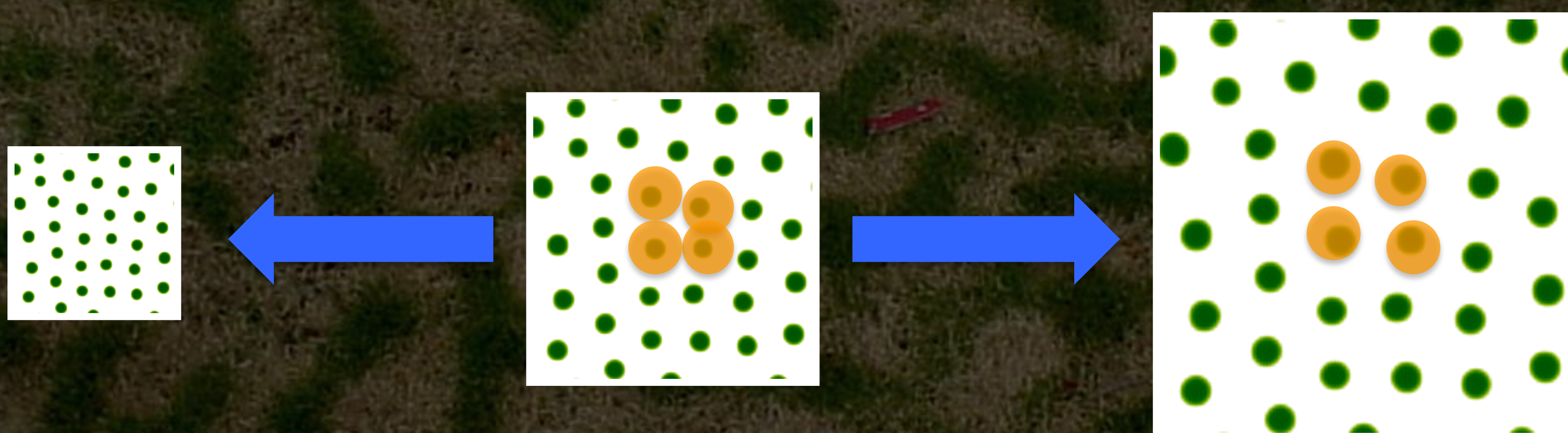
L=3.75m

L=6m

Natural vs. imposed patterns

$\partial b/\partial t = 0$



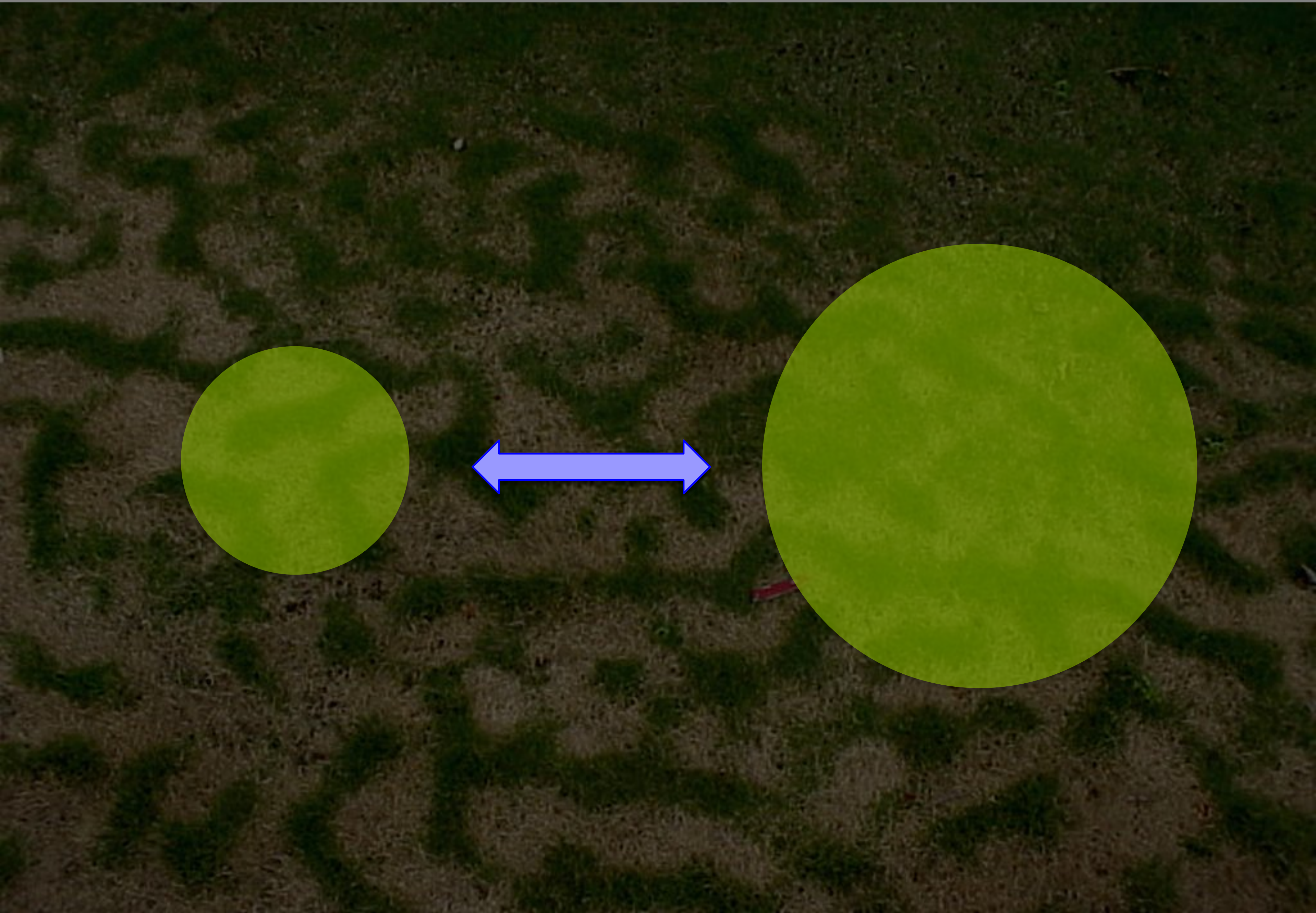


L=2m

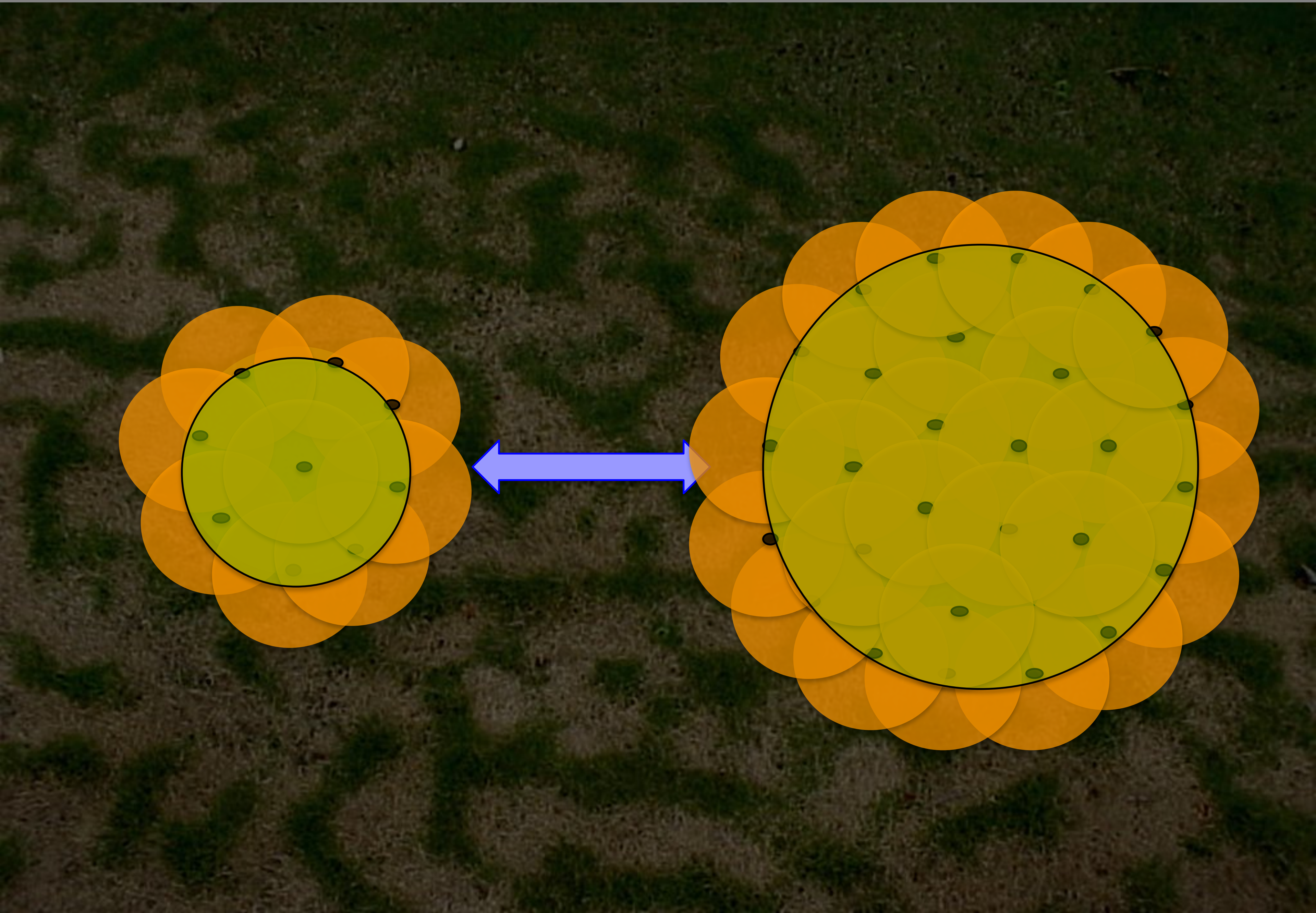
L=3.75m

L=6m

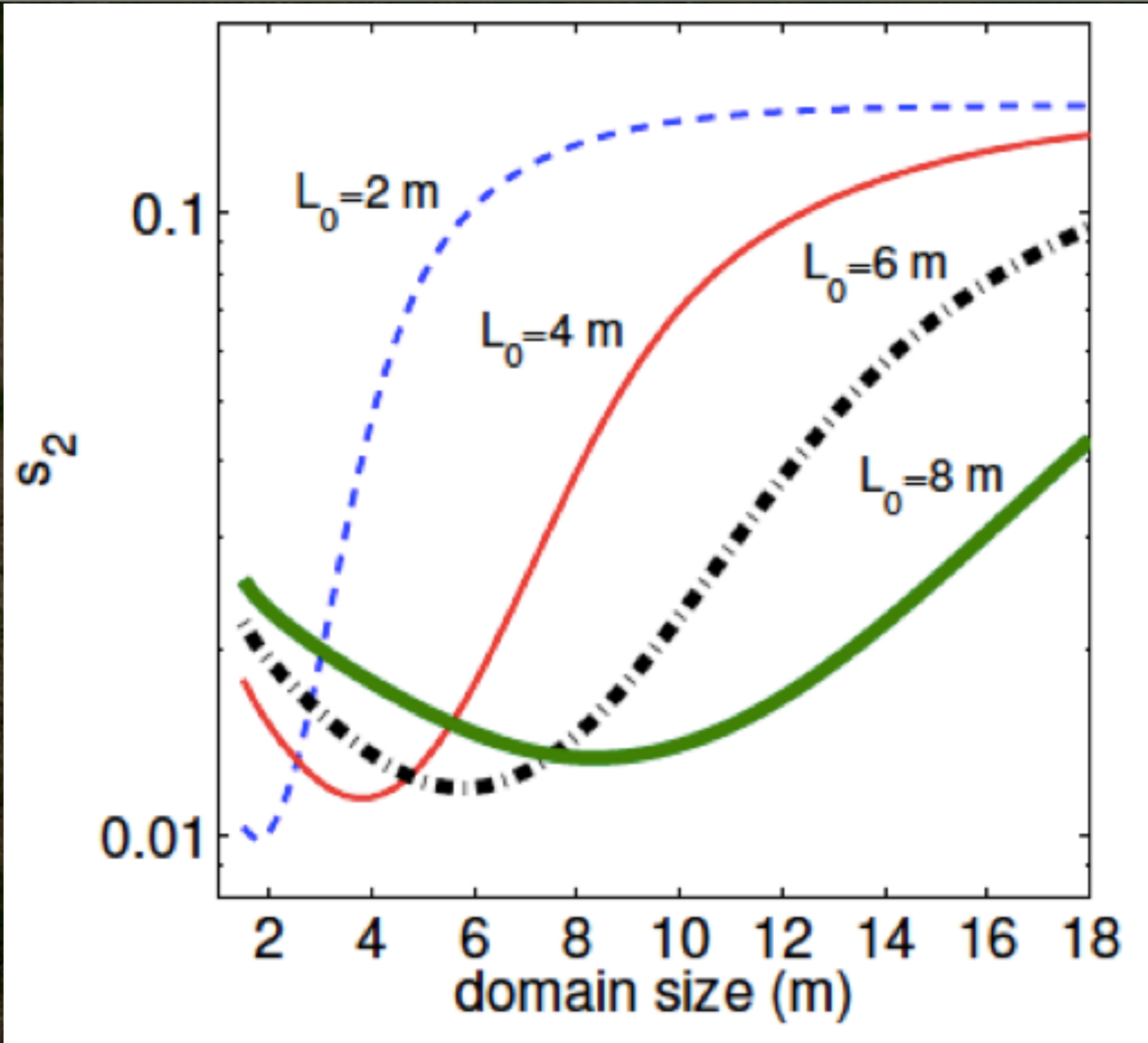
Role of root uptake mechanism



Natural vs. imposed patterns



Starting from dynamical patterns at different sizes



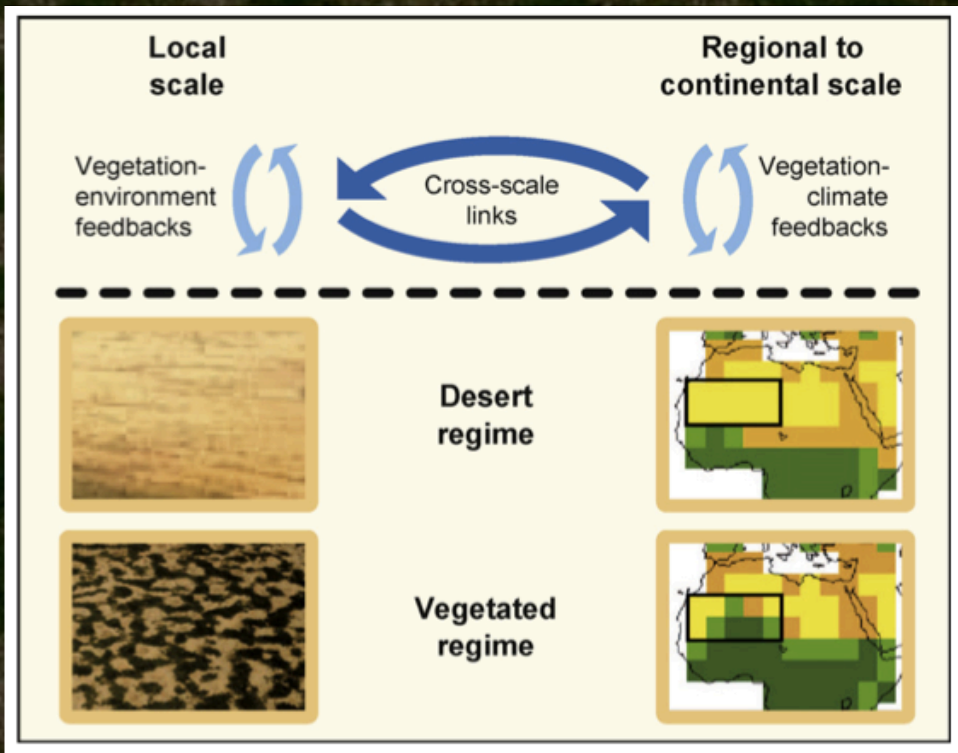
The upscaling issue

- The pattern state affects transpiration rates in the few days after an event

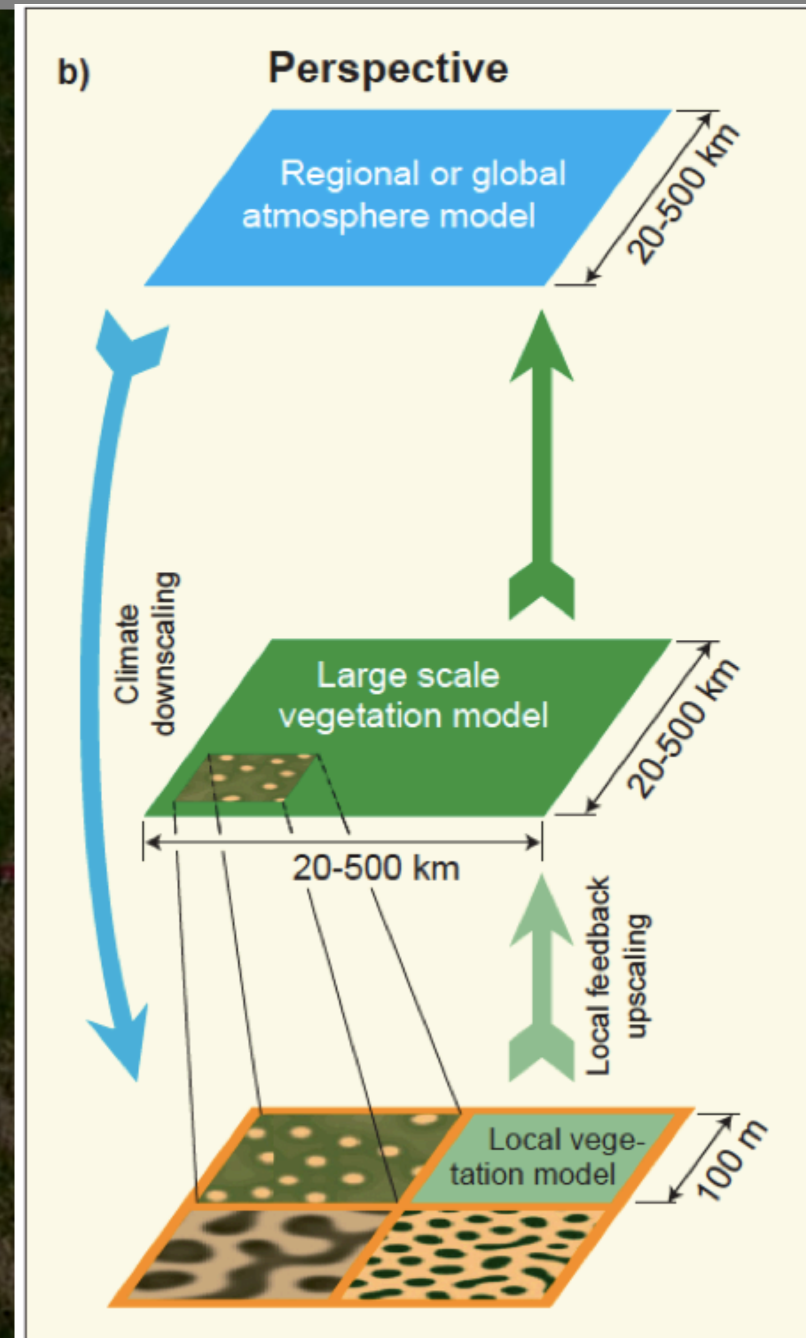
→ Moisture fluxes are dependent on the local water vegetation dynamics, as well as on the history of the system

→ Relevant for upscaling vegetation dynamics and for representing vegetation in large-scale models

The upscaling problem



Rietkerk, M. et al. (2011) Ecological Complexity 8 (3):223-228



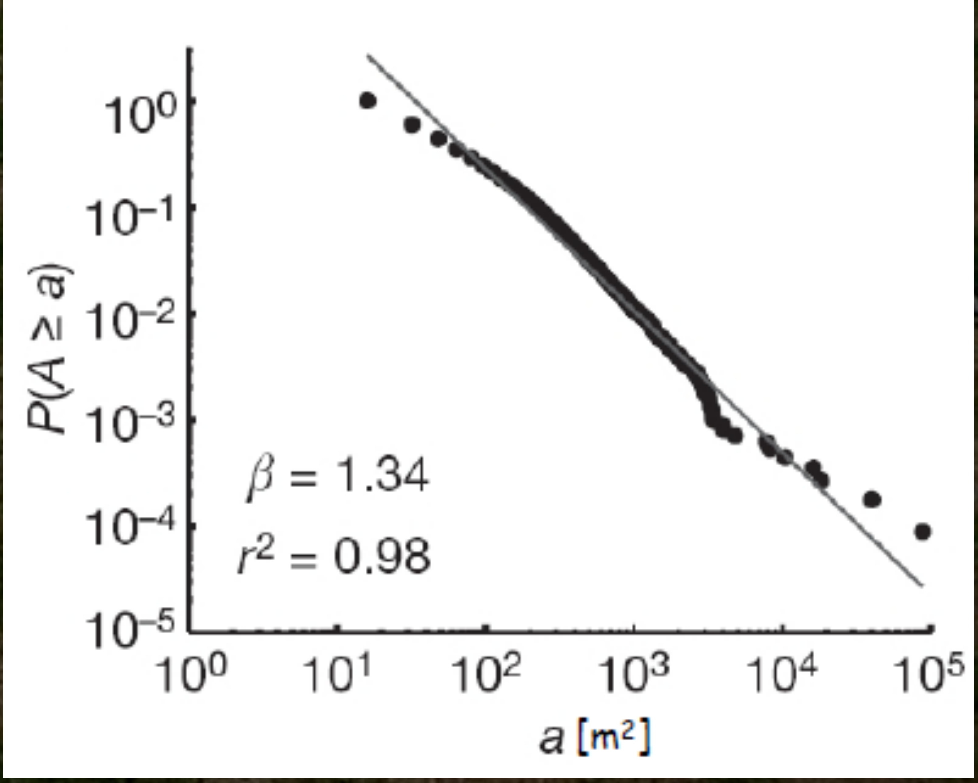
Dryland vegetation and intermittent precipitation

- Simple mathematical models suggest that changes in the variability of precipitation may impact significantly on the resilience of dryland vegetation
- Impact is stronger when vegetation is not using local feedbacks (the benefits are not cumulative)
- Different alternative strategies possible: e.g. nonlinear water uptake vs. use of infiltration feedback
- Model results suggest that transpiration may vary with pattern, due to competition in root uptake from bare soil → dependence of moisture fluxes on system dynamics and history
- The small-scale spatial structure of vegetation and its dynamics may have to be considered in developing parametrizations for large scale models

Scale-free patch size distributions

Satellite image
(Pandamatenga, Botswana)

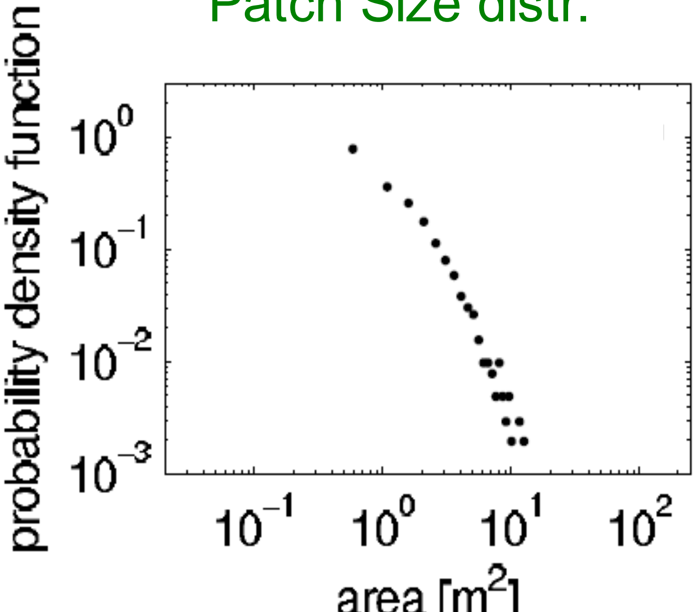
Patch size distribution



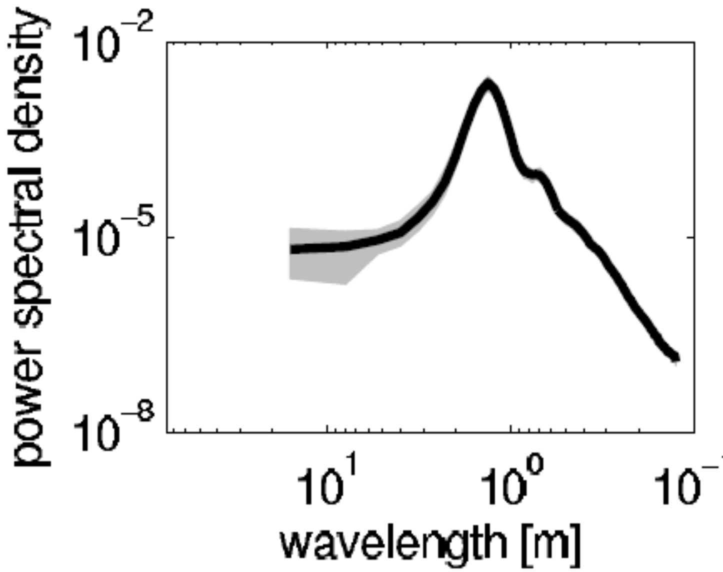
Scanlon et al. Nature **449** (2007)

Mixed states

Patch Size distr.

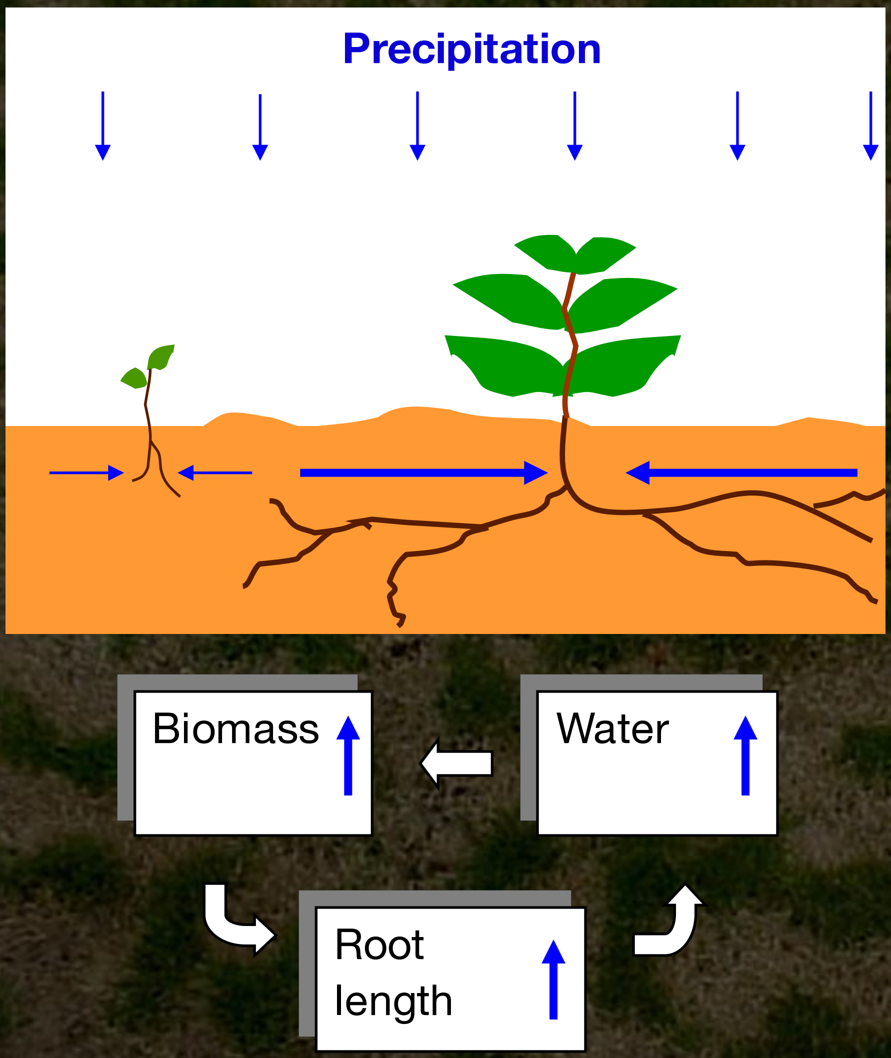


Spatial p. spectrum

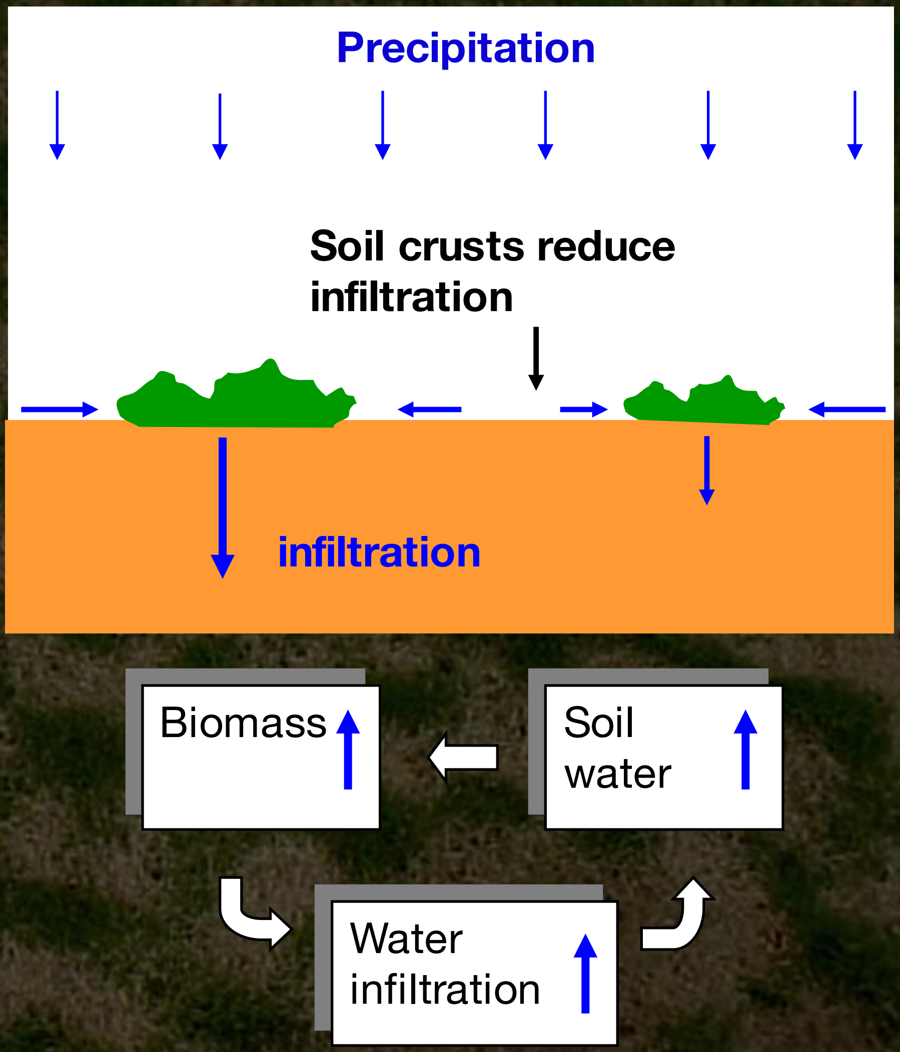


Dryland vegetation – Local feedback Mechanisms

Root uptake feedback
Long range competition

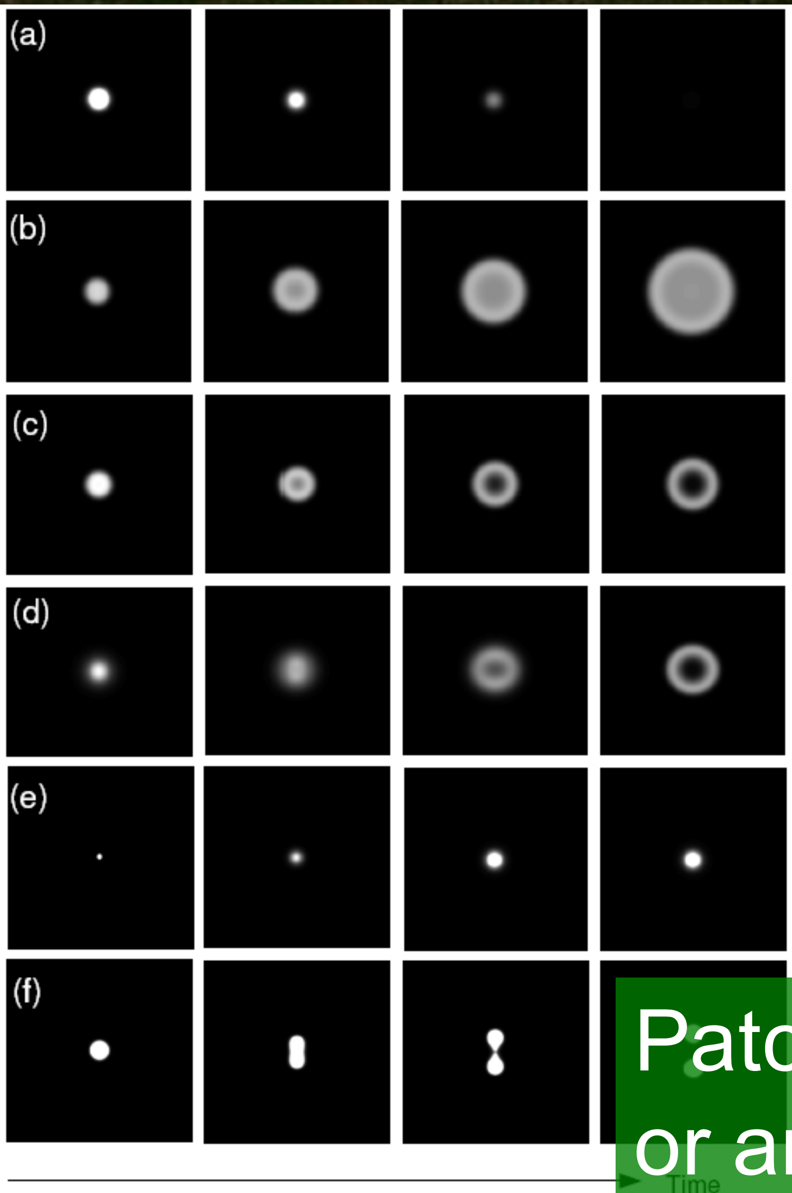


Infiltration feedback
Local facilitation +
Long range competition



Single patch dynamics

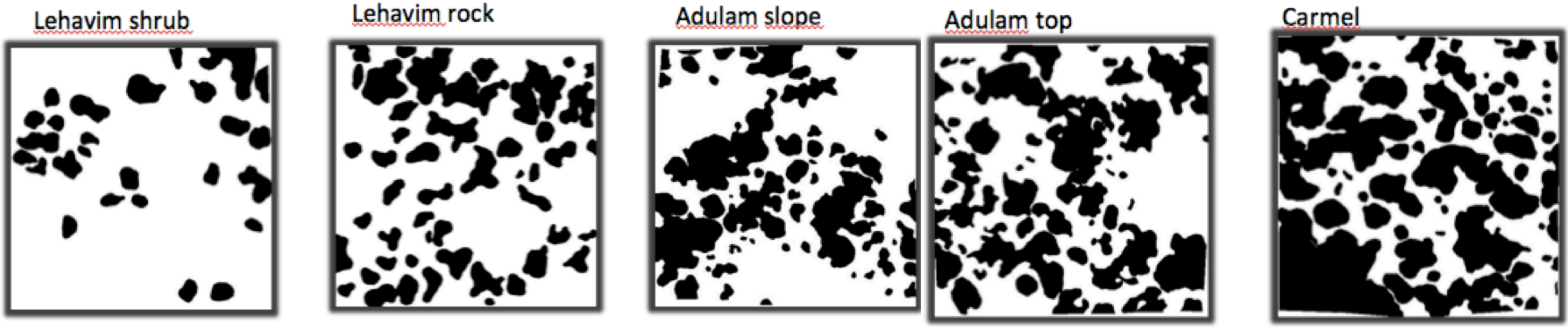
(H. Yizhaq + J. Nathan)

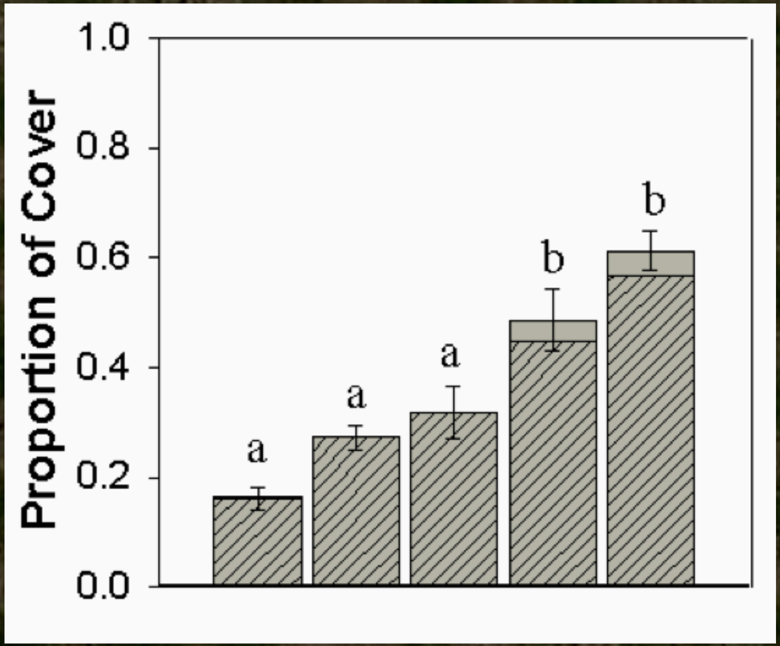


Infiltration FB	Root FB	Precip.
OFF	OFF	Low
OFF	OFF	High
ON	OFF	Low
OFF	ON	High
OFF	ON	Low

Patches either grow indefinitely or are limited in size

Fraction of cover function of precipitation





Precipitation →

Sissanit patterns from 5 sites in Israel

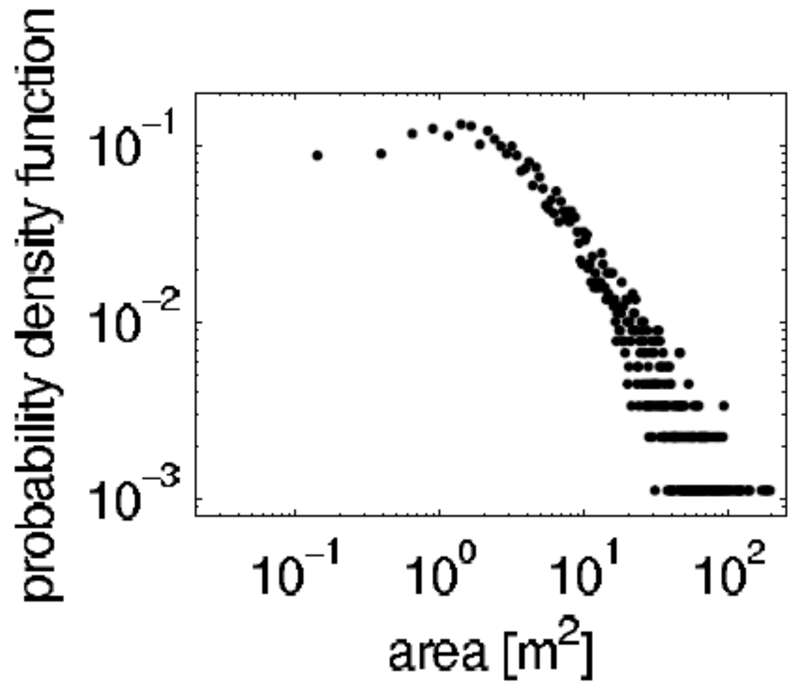
How can we obtain wide patch size distributions?

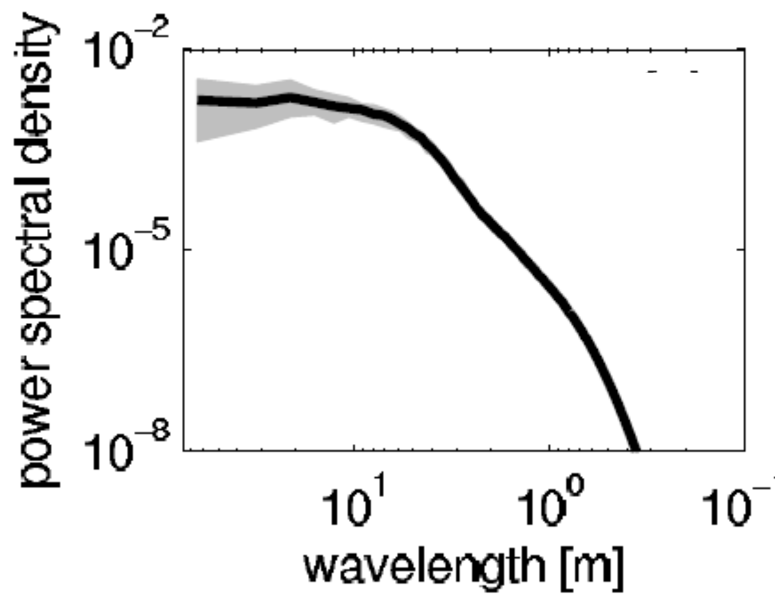
- Local (short-range) facilitation is needed in order to accelerate patch growth,
  but without long-range competition the system evolves towards uniform states (bare or uniform vegetation)
- Long-range competition limits patch size
- A global constraint is also needed!
- We can get a global constraint in our model increasing the range of the infiltration feedback, allowing water to reach the center of large patches
- Small patches stop growing when the water supply is exhausted globally

Scale-free patch size distributions

Global water redistribution mechanism:
soil infiltration time scale slower than overland water flow

$$E = 0, D_H = \infty, f = 0.1$$

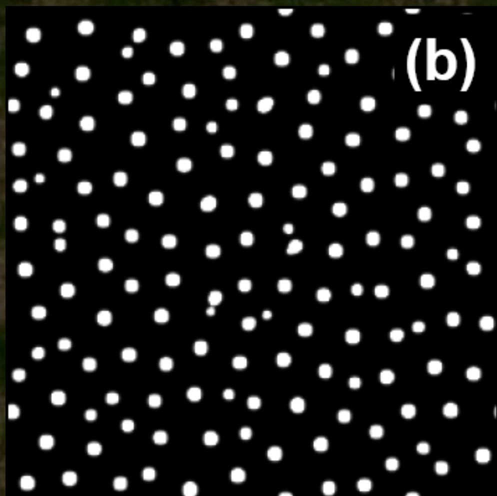


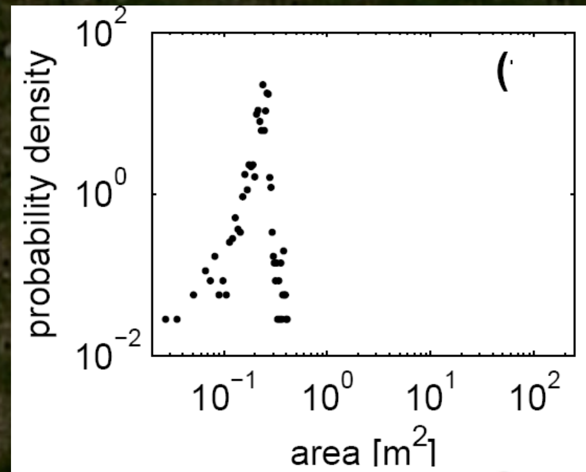


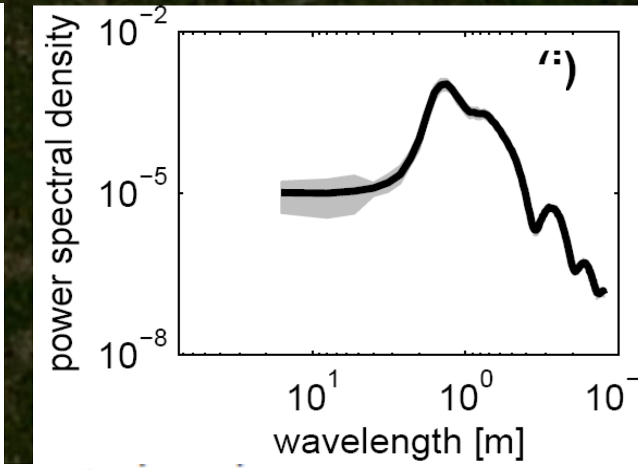
Turning back on feedbacks that limit patch size (root uptake or infiltration feedbacks)

Patch Size distr. | Spatial p. spectrum

w. Root Uptake FB

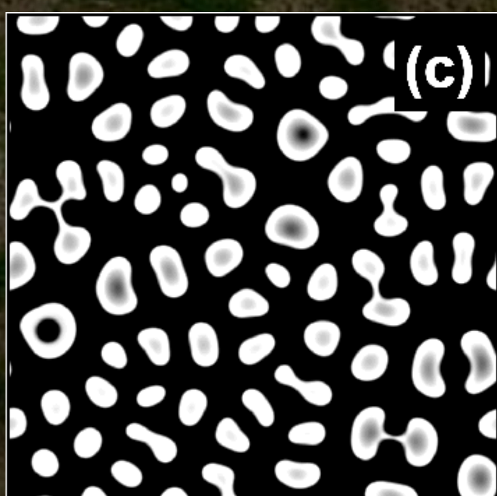


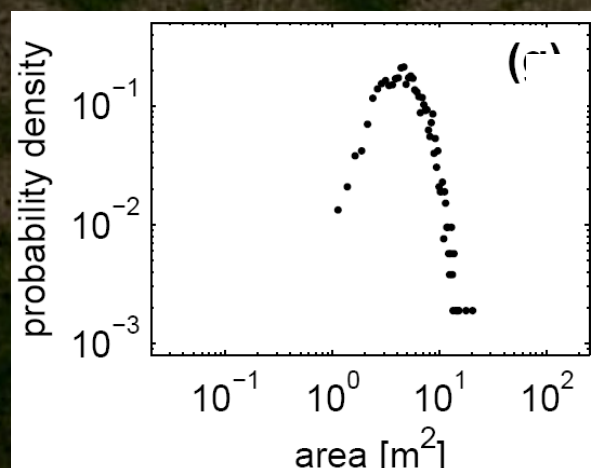


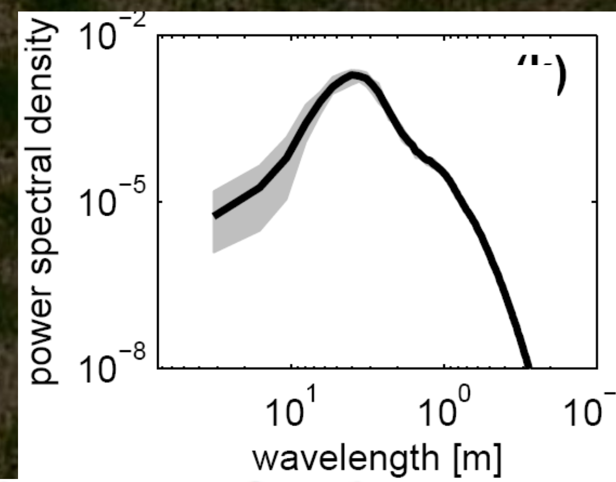


$E = 4\ \mathrm{m}^2\ \mathrm{kg}^{-1},\ D_{\mathrm{H}} = \infty,\ f = 0.1$

w. Infiltration FB



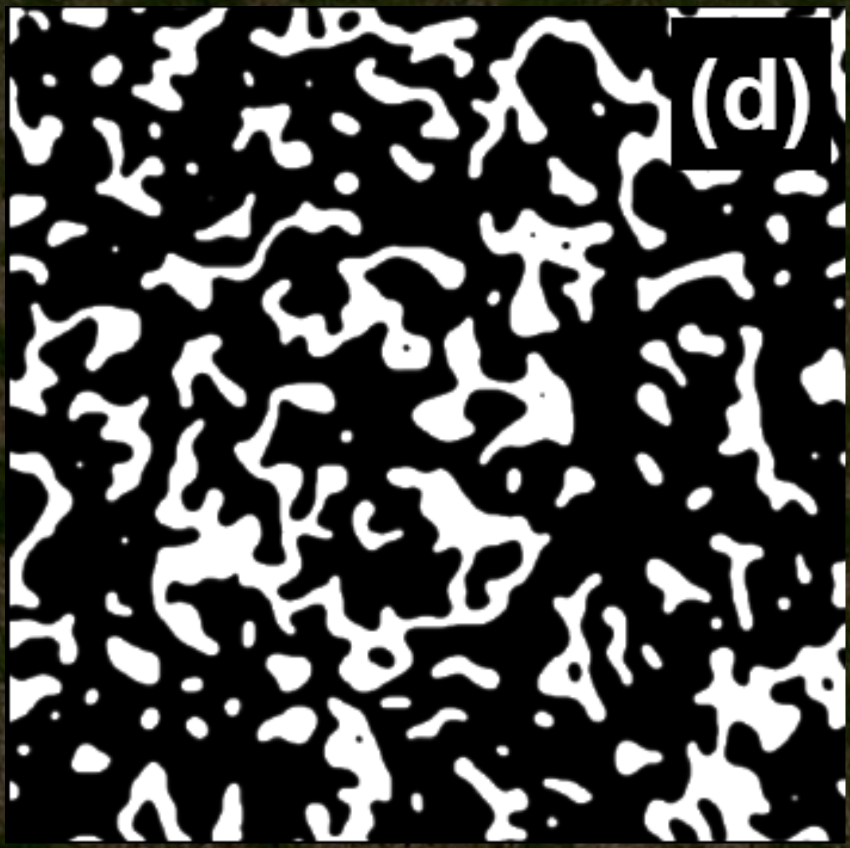




$E = 0,\ D_{\mathrm{H}} = 1\ \mathrm{m}^2\ \mathrm{y}^{-1}\ (\mathrm{kg\ m}^2)^{-1},\ f = 0.1$

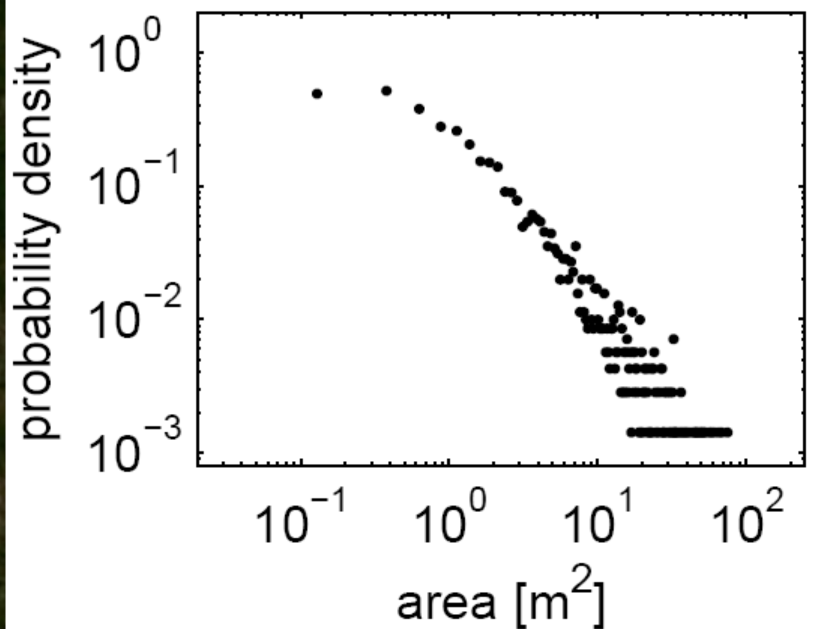
Wide patch size distributions

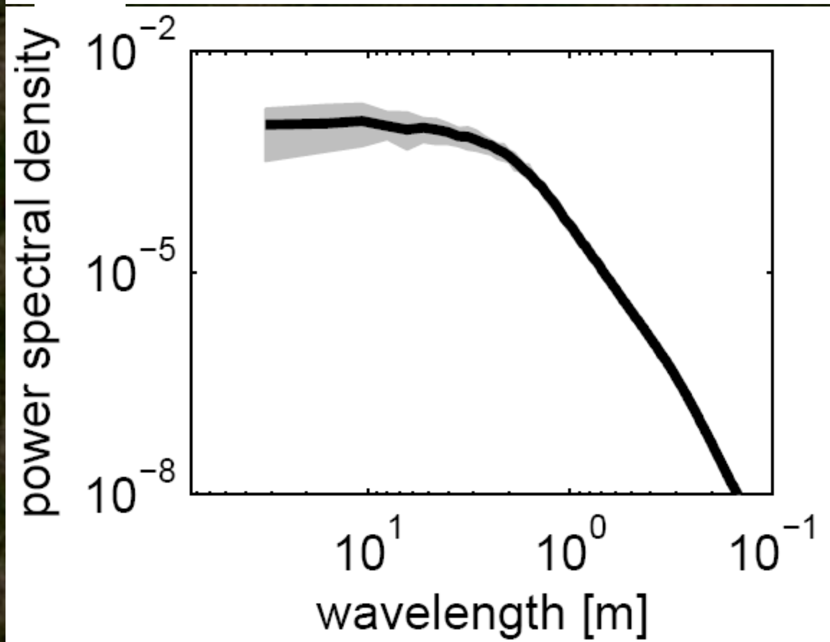
Or ….



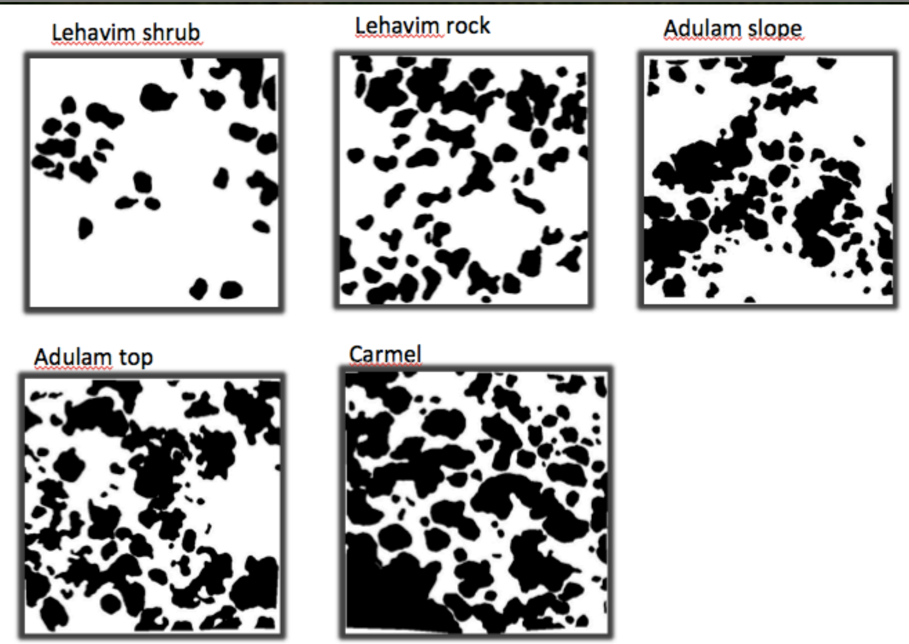
Global water redistribution mechanism:
Fast soil water diffusion

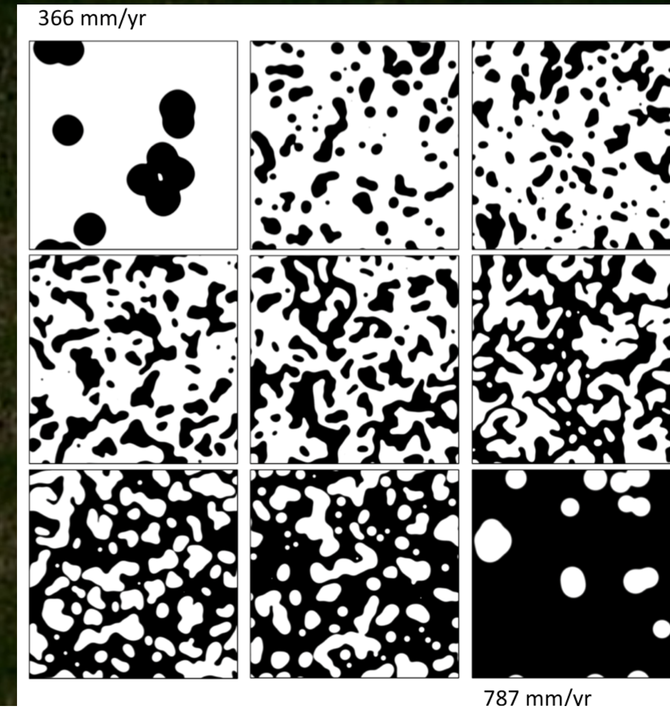
$$E = 2, \; D_W = \infty, \; f = 1$$

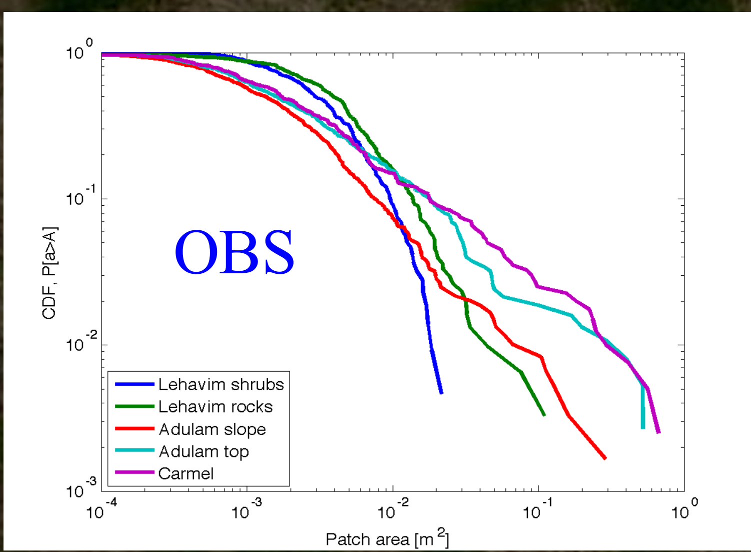


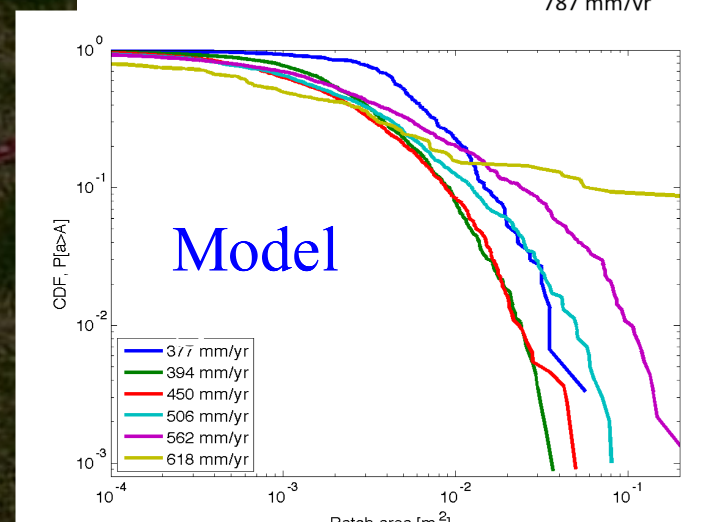


Comparison with observations (*Poa bulbosa L.*)









Efrat Sheffer, Jost von Hardenberg, Hezi Yizhaq, Moshe Shachak, Ehud Meron
Self-organization of disordered vegetation patchiness, in preparation

To conclude

Wide patch size distributions
(no typical scale) possible if:

- Small competition at a local scale
- Global/large scale redistribution of the resource (by runoff or diffusion)
- Uniform coverage is not possible

Rainfall manipulation experiments

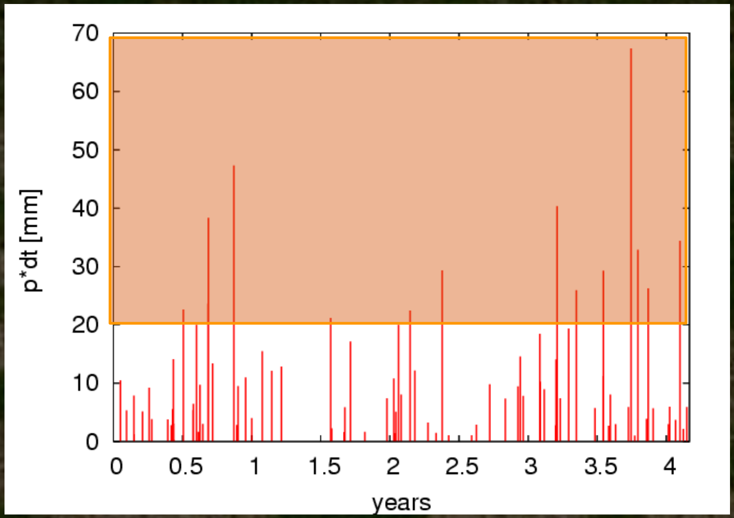
- Several manipulation experiments are underway to study the ecological impacts of climate changes in rainfall average and temporal distribution
- Most experiments are rainfall exclusion or addition experiments (manipulating the average and simulating droughts)
- Few study precipitation variability
- In order to test some of the results discussed above, an adequate representation of realistic changes in precipitation variability is needed

Rain-out shelter

From: Fraser et al. *Front Ecol Environ* 2013, 11(3): 147–155

See also:
Beier, C et al. (2012) Ecology Letters, **15**, 899–911

Design of rainfall manipulation experiments



Issues in the design of experiments with realistic precipitation changes:

e.g.: simply reducing average precipitation will also lead to a reduction in variability

Precipitation has typically a distribution with long exponential tails:

$$f(x) = \lambda e^{-\lambda x}$$

$$\mathrm{Var}[X] = \frac{1}{\lambda^2} \quad \mathrm{E}[X] = \frac{1}{\lambda}$$

A reduction in the mean will be accompanied by a reduction in variance