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WETLANDS CONFERENCE

WETLANDS IN A COMPLEX WORLD

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Topographic and Self-Organizing Controls Over Wetland Dynamics

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Wetland Ecosystems

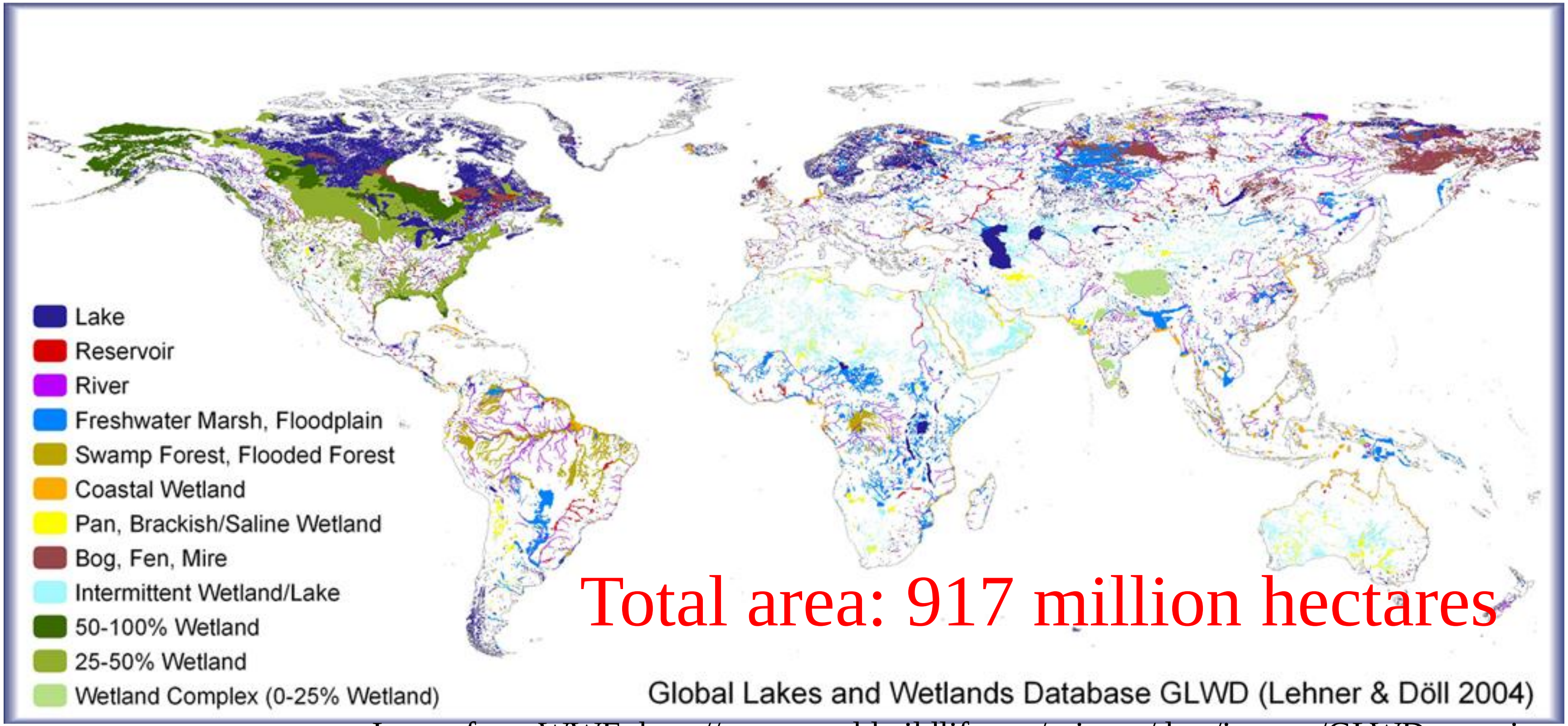


Image from WWF: http://www.worldwildlife.org/science/data/images/GLWD_map.jpg

North Europe and North America

- 34% of world total area (*Millennium Ecosystem Assessment*, 2008)
- 15 – 30% of global peat carbon in boreal and subarctic peatlands (*Limpens et al*, 2008)

Asia

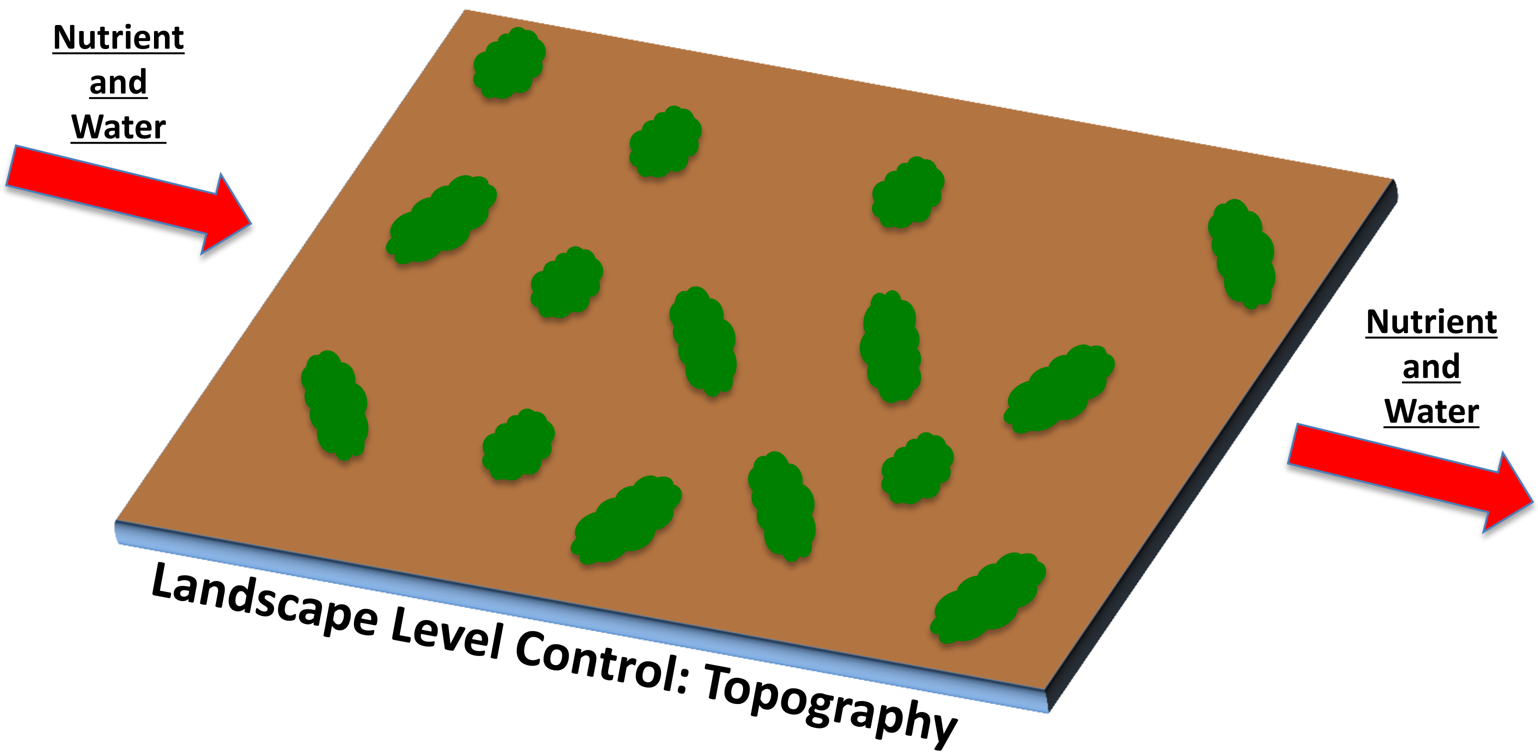
- 31% world total area (*Millennium Ecosystem Assessment*, 2008)
- 15 – 19% of global peat carbon in Southeast Asia tropical peatlands (*Page et al*, 2010)

Topographic Control

Topography controls downslope flow of resources (i.e. water and nutrients).

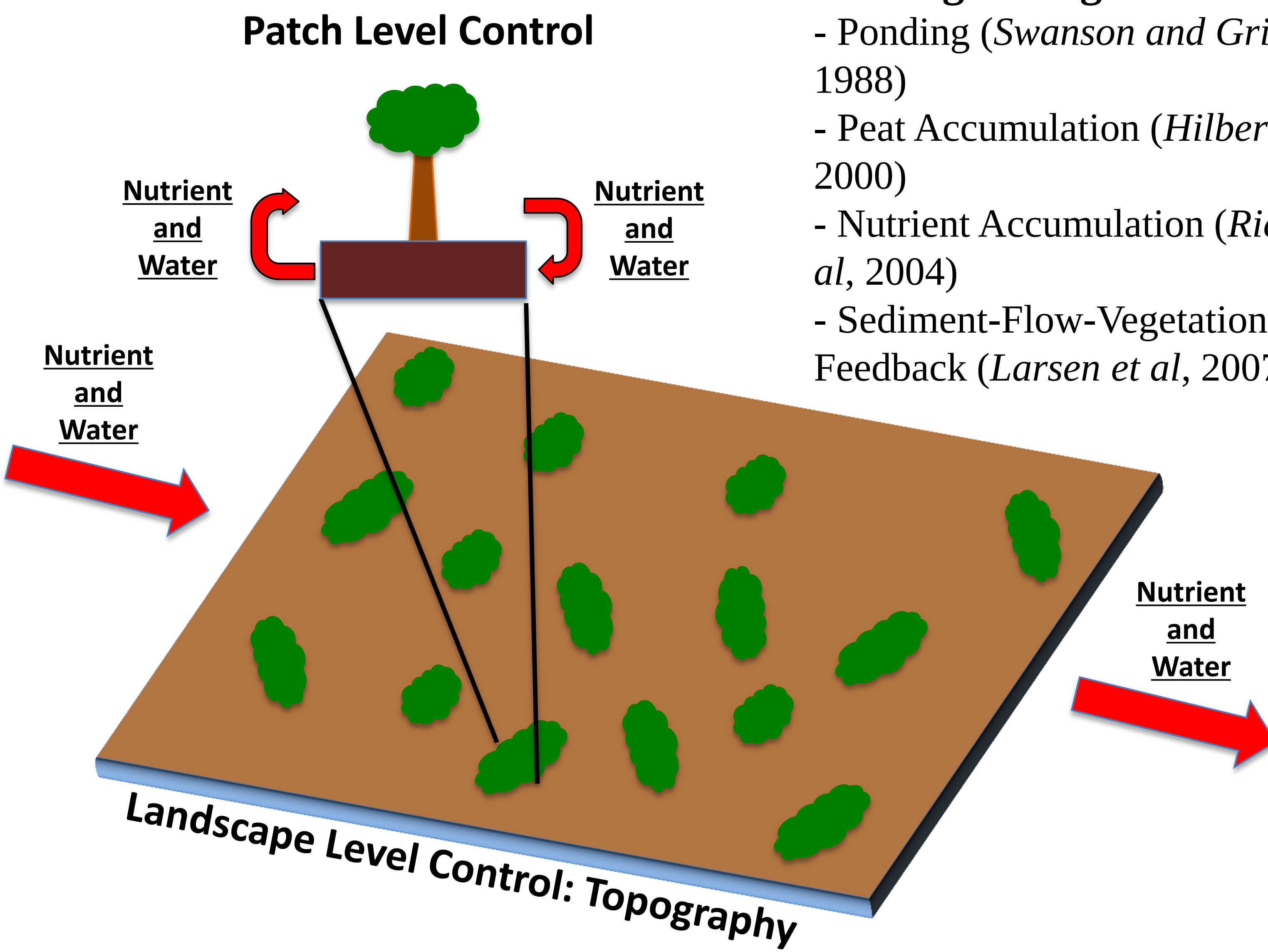
Topography affects wetness (water table depth and soil moisture content), evapotranspiration and gross ecosystem productivity (*Sonnentag et al*. 2008).

Study in Mer Bleue peatland, Canada showed that model underestimate daily ET and gross ecosystem productivity by ~10 – 12% when topographically driven lateral subsurface fluxes were neglected from the model framework (*Sonnentag et al*. 2008).



Self-Organizing Controls

Through spatial feedbacks, vegetation is able to actively modify its environment and maximize resource flows towards it.



Self-organizing mechanisms:

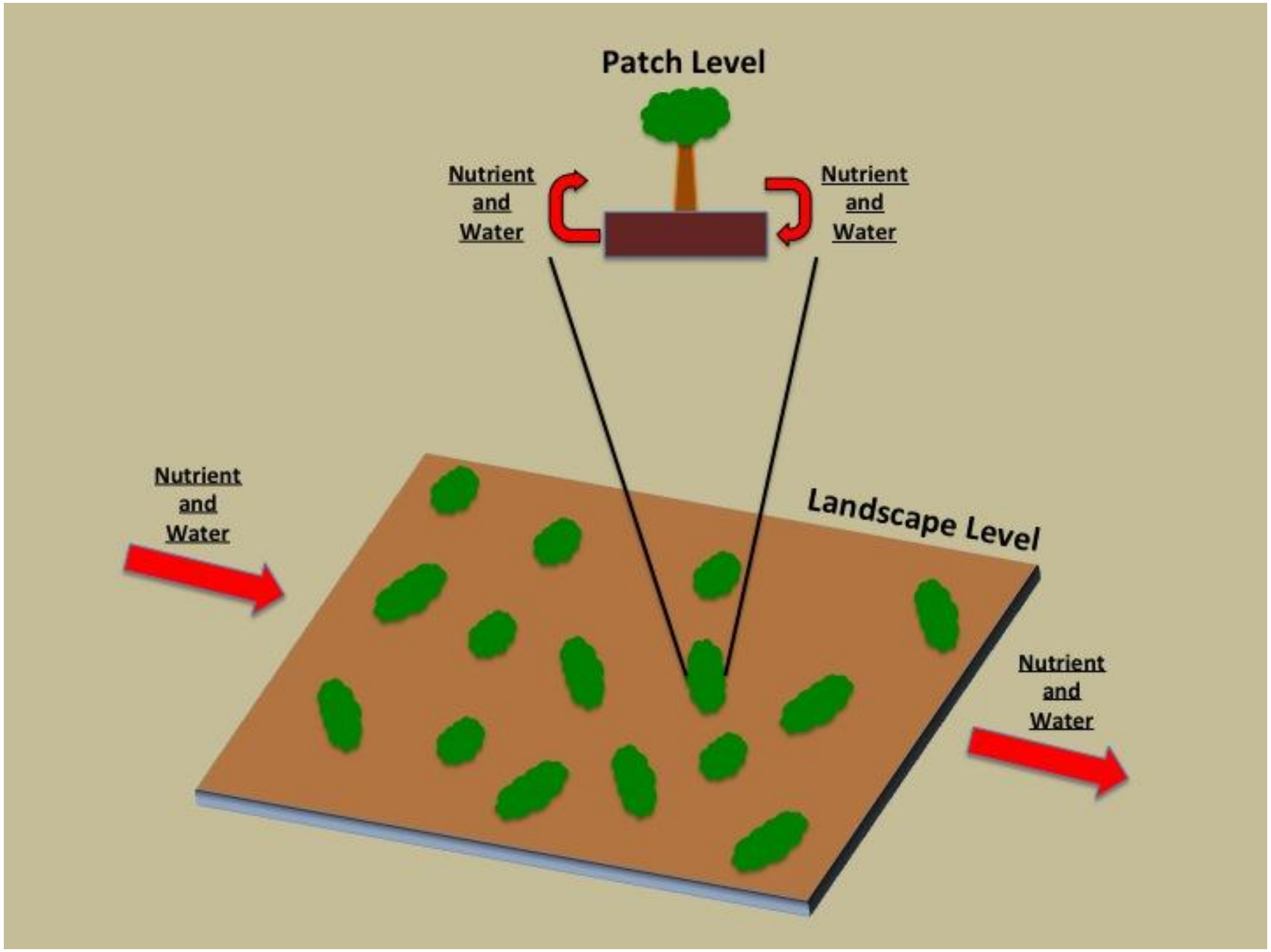
- Ponding (*Swanson and Grigal*, 1988)
- Peat Accumulation (*Hilbert et al*, 2000)
- Nutrient Accumulation (*Rietkerk et al*, 2004)
- Sediment-Flow-Vegetation Feedback (*Larsen et al*, 2007)

Objectives

Demonstrate how these first order controls (Topography and self-organizing mechanisms) together can impact:

(1) spatial vegetation patterning

(2) vegetation growth dynamics of a nutrient limited ecosystem



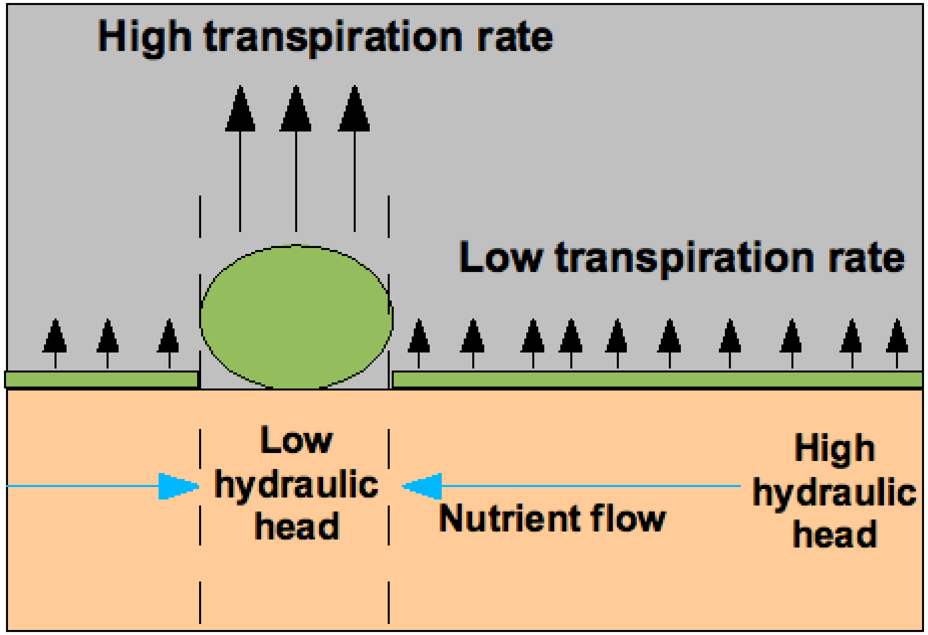
Nutrient Accumulation Mechanism

Proposed by *Rietkerk et al* (2004) to explain pattern formation in bogs.

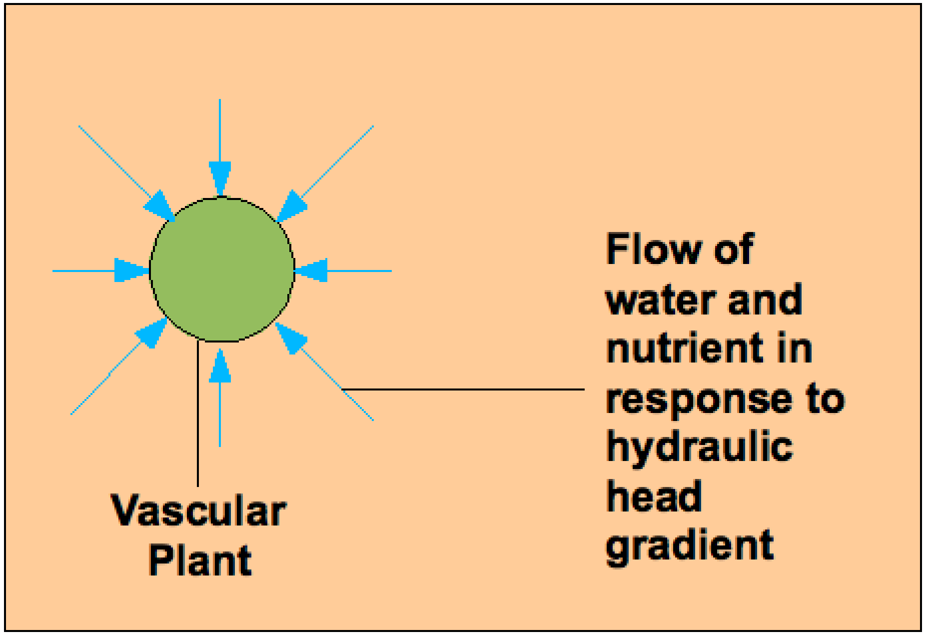
Self-organization caused by convective transport of nutrients in the groundwater toward areas with higher vascular plant biomass, driven by differences in transpiration rate.

For a flat terrain:

Side View



Top View



Governing Equations

Plant Biomass, *B*

$$\frac{\partial B}{\partial t} = \gamma \cdot [N] \cdot B \cdot f[\eta(H)] - \delta \cdot B - \beta \cdot B + D_B \cdot \left[\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2}\right]$$

[Nutrient limited growth] **[Mortality]** **[Diffusion]**

Hydraulic Head, *H*

$$\frac{\partial H}{\partial t} = \frac{p}{\theta} - \frac{\tau_v \cdot B \cdot f[\eta(H)]}{\theta} - \frac{\varepsilon \cdot f[\eta(H)]}{\theta} + \frac{k_x}{\theta} \cdot \left[\frac{\partial}{\partial x}\left(H \cdot \frac{\partial H}{\partial x}\right)\right] + \frac{k_y}{\theta} \cdot \left[\frac{\partial}{\partial y}\left(H \cdot \frac{\partial H}{\partial y} + H \cdot \frac{\partial c}{\partial y}\right)\right]$$

[Ppt] **[Transpiration]** **[Evaporation]** **[Advection]**

Nutrient, [*N*]

$$\frac{\partial [N]}{\partial t} = \frac{N_i - \mu [N] \cdot B \cdot f[\eta(H)] + \delta \cdot \left(\frac{\mu}{\gamma}\right) \cdot B - r \cdot N - [N] \cdot \theta \cdot \frac{\partial H}{\partial t}}{H \cdot \theta}$$

[Anthropogenic input, plant uptake, recycling of dead biomass, nutrient loss]

$$+ D_N \cdot \left[\frac{\partial^2 [N]}{\partial x^2} + \frac{\partial^2 [N]}{\partial y^2}\right] + \frac{k_x}{\theta} \cdot \left[\frac{\partial}{\partial x}\left([N] \cdot \frac{\partial H}{\partial x}\right)\right] + \frac{k_y}{\theta} \cdot \left[\frac{\partial}{\partial y}\left([N] \cdot \frac{\partial H}{\partial y} + [N] \cdot \frac{\partial c}{\partial y}\right)\right]$$

[Diffusion] **[Advection]**

Governing Equations: Advection

$$\frac{\partial B}{\partial t} = g \cdot [N] \cdot B \cdot f[h(H)] - d \cdot B - b \cdot B + D_B \cdot [\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2}]$$

$$\frac{\partial H}{\partial t} = \frac{p}{q} - \frac{t_v \cdot B \cdot f[h(H)]}{q} - \frac{e \cdot f[h(H)]}{q} + \frac{k_x}{q} \cdot \left[\frac{\partial}{\partial x}\left(H \cdot \frac{\partial H}{\partial x}\right)\right] + \frac{k_y}{q} \cdot \left[\frac{\partial}{\partial y}\left(H \cdot \frac{\partial H}{\partial y} + H \cdot \frac{\partial c}{\partial y}\right)\right]$$

$$\frac{\partial [N]}{\partial t} = \frac{N_i - m[N] \cdot B \cdot f[h(H)] + d \cdot (\frac{m}{g}) \cdot B - r \cdot N - [N] \cdot q \cdot \frac{\partial H}{\partial t}}{H \cdot q}$$

$$+ D_N \cdot \left[\frac{\partial^2 [N]}{\partial x^2} + \frac{\partial^2 [N]}{\partial y^2}\right] + \frac{k_x}{q} \cdot \left[\frac{\partial}{\partial x}\left([N] \cdot \frac{\partial H}{\partial x}\right)\right] + \frac{k_y}{q} \cdot \left[\frac{\partial}{\partial y}\left([N] \cdot \frac{\partial H}{\partial y} + [N] \cdot \frac{\partial c}{\partial y}\right)\right]$$

Global advection due to topography.
Cheng et al, 2011 (GRL).

Governing Equations: Diffusion

$$\frac{\partial B}{\partial t} = g \cdot [N] \cdot B \cdot f[h(H)] - d \cdot B - b \cdot B + \boxed{D_B \cdot \left[\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2}\right]}$$

$$\frac{\partial H}{\partial t} = \frac{p}{\theta} - \frac{t_v \cdot B \cdot f[h(H)]}{\theta} - \frac{e \cdot f[h(H)]}{\theta} + \frac{k_x}{\theta} \cdot \left[\frac{\partial}{\partial x}\left(H \cdot \frac{\partial H}{\partial x}\right)\right] + \frac{k_y}{\theta} \cdot \left[\frac{\partial}{\partial y}\left(H \cdot \frac{\partial H}{\partial y} + H \cdot \frac{\partial c}{\partial y}\right)\right]$$

$$\frac{\partial [N]}{\partial t} = \frac{N_i - \mu[N] \cdot B \cdot f[h(H)] + d \cdot \left(\frac{\mu}{\gamma}\right) \cdot B - r \cdot N - [N] \cdot \theta \cdot \frac{\partial H}{\partial t}}{H \cdot \theta}$$

$$\boxed{+ D_N \cdot \left[\frac{\partial^2 [N]}{\partial x^2} + \frac{\partial^2 [N]}{\partial y^2}\right]} + \frac{k_x}{\theta} \cdot \left[\frac{\partial}{\partial x}\left([N] \cdot \frac{\partial H}{\partial x}\right)\right] + \frac{k_y}{\theta} \cdot \left[\frac{\partial}{\partial y}\left([N] \cdot \frac{\partial H}{\partial y} + [N] \cdot \frac{\partial c}{\partial y}\right)\right]$$

Governing Equations: Reaction

$$\frac{\partial B}{\partial t} = \boxed{g \cdot [N] \cdot B \cdot f[h(H)] - d \cdot B - b \cdot B} + D_B \cdot \left[\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2}\right]$$

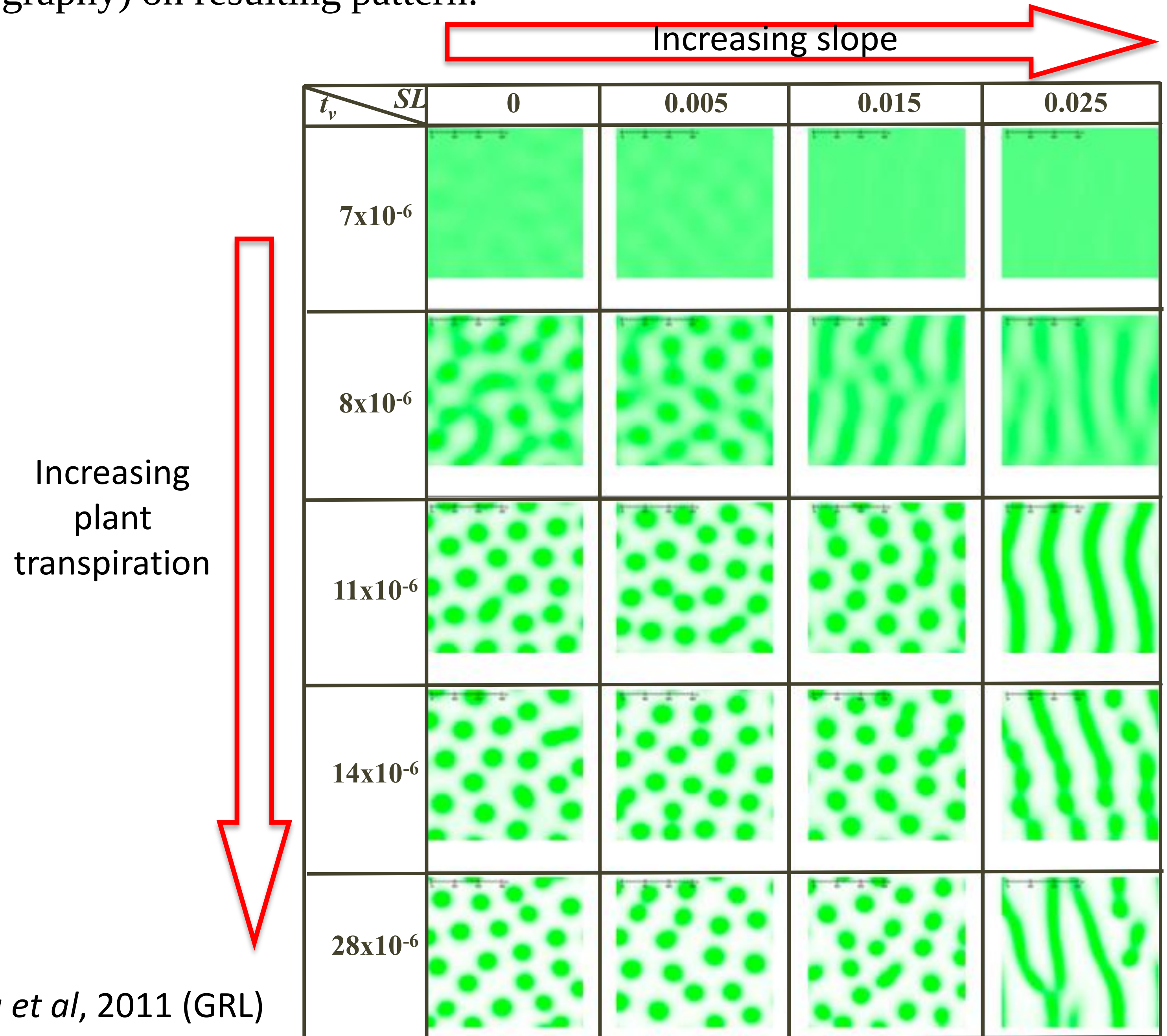
$$\frac{\partial H}{\partial t} = \boxed{\frac{p}{\theta} - \frac{t_v \cdot B \cdot f[h(H)]}{\theta} - \frac{e \cdot f[h(H)]}{\theta}} + \frac{k_x}{\theta} \cdot \left[\frac{\partial}{\partial x}\left(H \cdot \frac{\partial H}{\partial x}\right)\right] + \frac{k_y}{\theta} \cdot \left[\frac{\partial}{\partial y}\left(H \cdot \frac{\partial H}{\partial y} + H \cdot \frac{\partial c}{\partial y}\right)\right]$$

$$\frac{\partial [N]}{\partial t} = \boxed{\frac{N_i - \mu [N] \cdot B \cdot f[h(H)] + d \cdot \left(\frac{\mu}{g}\right) \cdot B - r \cdot N - [N] \cdot \theta \cdot \frac{\partial H}{\partial t}}{H \cdot \theta}}$$

$$+ D_N \cdot \left[\frac{\partial^2 [N]}{\partial x^2} + \frac{\partial^2 [N]}{\partial y^2}\right] + \frac{k_x}{\theta} \cdot \left[\frac{\partial}{\partial x}\left([N] \cdot \frac{\partial H}{\partial x}\right)\right] + \frac{k_y}{\theta} \cdot \left[\frac{\partial}{\partial y}\left([N] \cdot \frac{\partial H}{\partial y} + [N] \cdot \frac{\partial c}{\partial y}\right)\right]$$

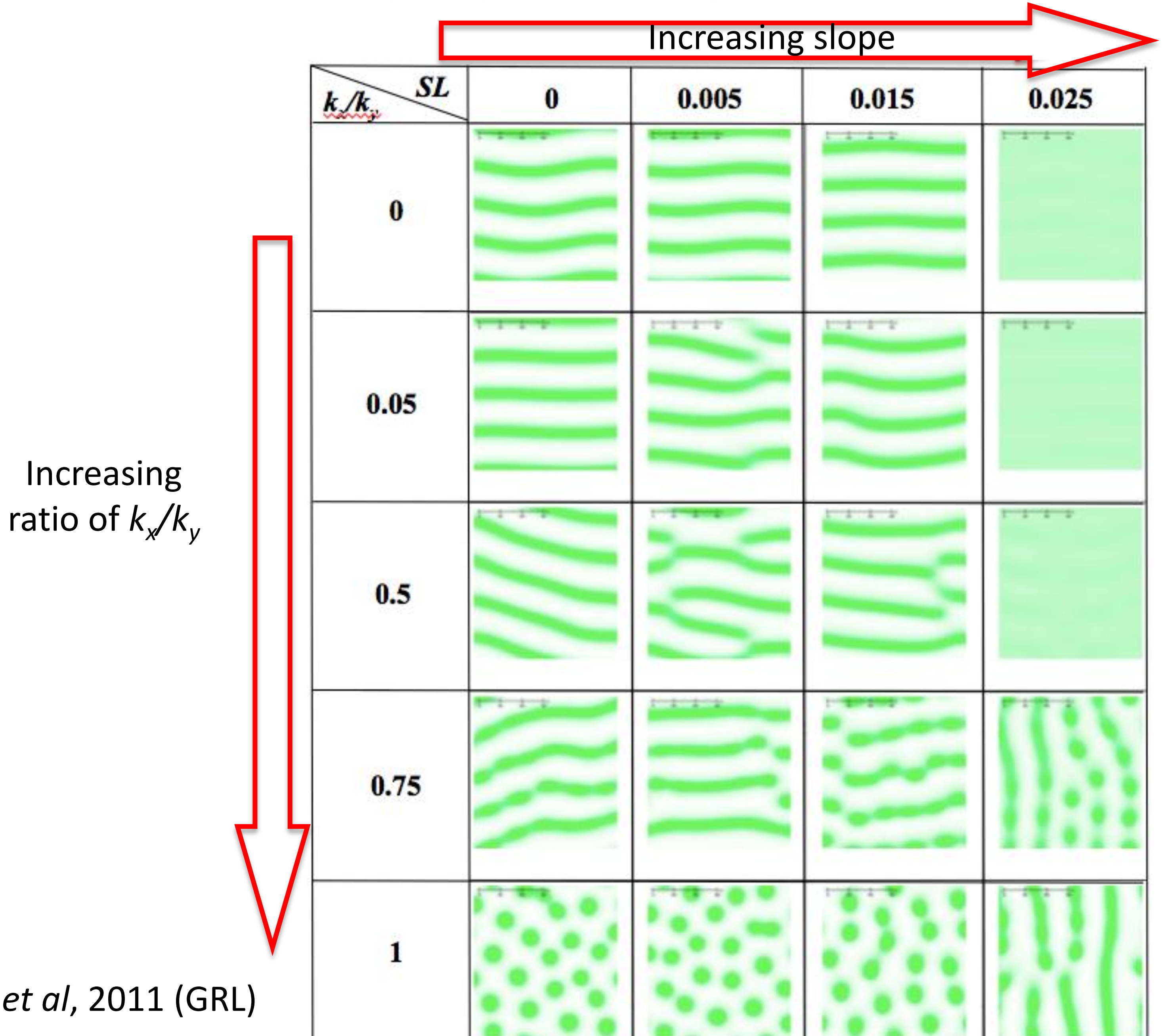
Spatial Patterning

Interactive effects of plant transpiration (self organizing mechanism) and slope (topography) on resulting pattern.



Cheng et al, 2011 (GRL)

Interactive effects of effective anisotropic hydraulic conductivity (self organizing mechanism) and slope (topography) on resulting pattern.



Cheng et al, 2011 (GRL)

Vegetation Growth Dynamics

Models

1. Topographic Control + Self-Organizing Control (TC + SO)

$$\frac{\partial H}{\partial t}=\frac{p}{\theta}-\frac{t_v\cdot B\cdot f[h(H)]}{\theta}-\frac{e\cdot f[h(H)]}{\theta}+\frac{k_x}{\theta}\cdot\left[\frac{\partial}{\partial x}\left(H\cdot\frac{\partial H}{\partial x}\right)\right]+\frac{k_y}{\theta}\cdot\left[\frac{\partial}{\partial y}\left(H\cdot\frac{\partial H}{\partial y}+H\cdot\frac{\partial c}{\partial y}\right)\right]$$

$$\frac{\partial[N]}{\partial t}=\frac{N_i-\mu[N]\cdot B\cdot f[h(H)]+d\cdot\left(\frac{\mu}{\gamma}\right)\cdot B-r\cdot N-[N]\cdot\theta\cdot\frac{\partial H}{\partial t}}{H\cdot\theta}$$

$$+D_N\cdot\left[\frac{\partial^2[N]}{\partial x^2}+\frac{\partial^2[N]}{\partial y^2}\right]+\frac{k_x}{\theta}\cdot\left[\frac{\partial}{\partial x}\cdot\left([N]\cdot\frac{\partial H}{\partial x}\right)\right]+\frac{k_y}{\theta}\cdot\left[\frac{\partial}{\partial y}\cdot\left([N]\cdot\frac{\partial H}{\partial y}+[N]\cdot\frac{\partial c}{\partial y}\right)\right]$$

2. Topographic Control (TC)

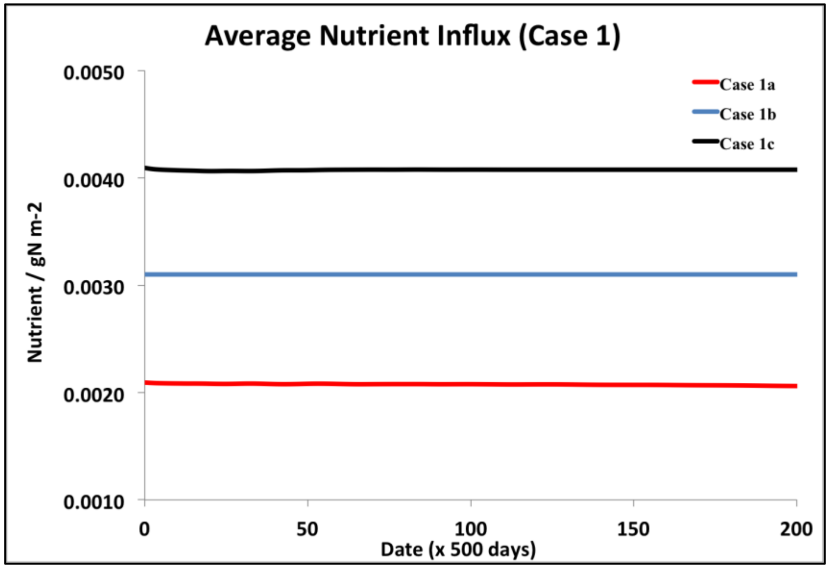
$$\frac{\partial H}{\partial t}=\frac{p}{\theta}-\frac{t_v\cdot B\cdot f[h(H)]}{\theta}-\frac{e\cdot f[h(H)]}{\theta}+\frac{k_x}{\theta}\cdot\left[\frac{\partial}{\partial x}\left(H\cdot\cancel{\frac{\partial H}{\partial x}}\right)\right]+\frac{k_y}{\theta}\cdot\left[\frac{\partial}{\partial y}\left(H\cdot\cancel{\frac{\partial H}{\partial y}}+H\cdot\frac{\partial c}{\partial y}\right)\right]$$

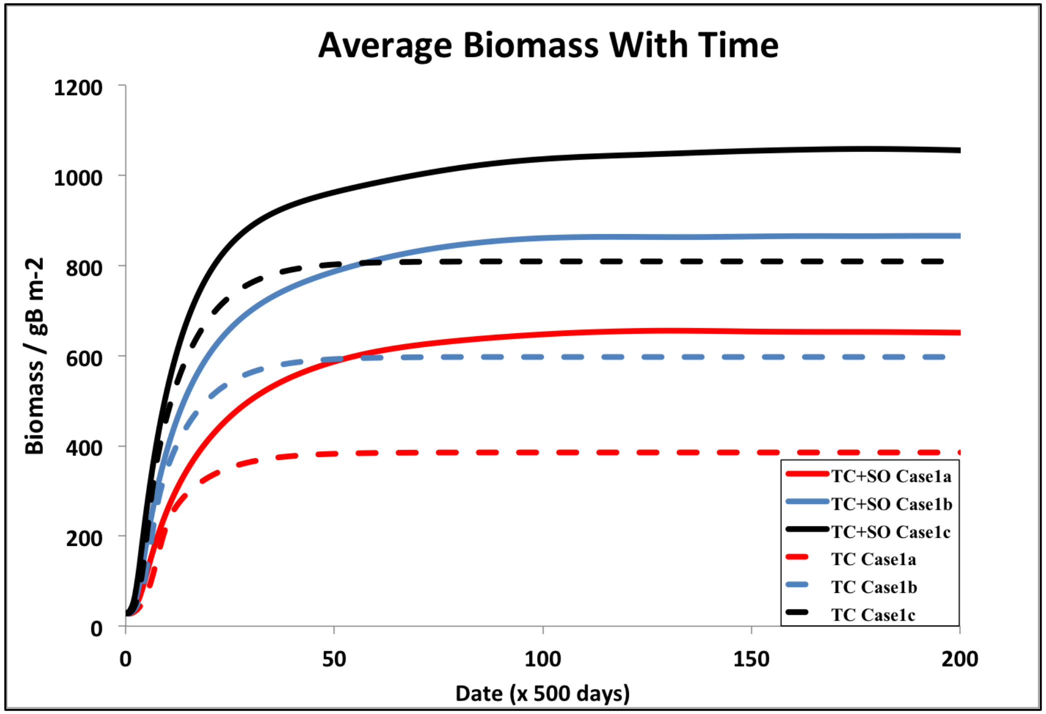
$$\frac{\partial[N]}{\partial t}=\frac{N_i-\mu[N]\cdot B\cdot f[h(H)]+d\cdot\left(\frac{\mu}{\gamma}\right)\cdot B-r\cdot N-[N]\cdot\theta\cdot\frac{\partial H}{\partial t}}{H\cdot\theta}$$

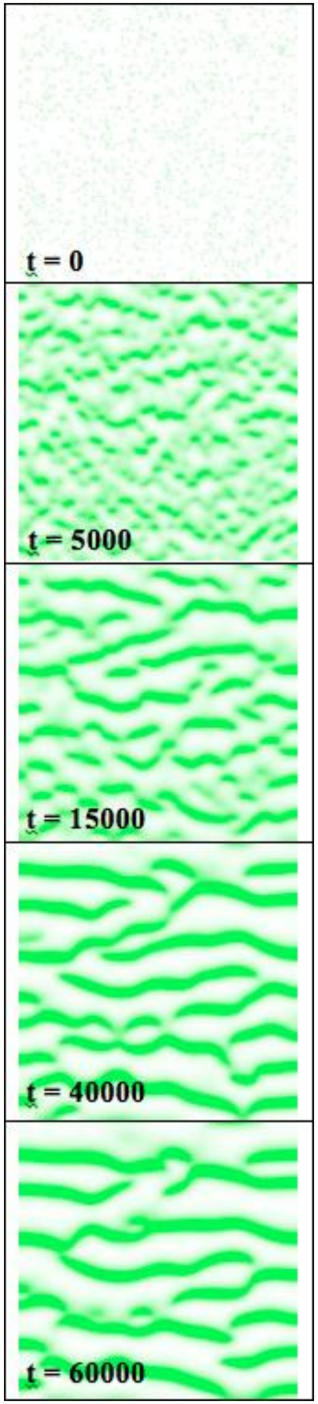
Local advection terms removed!

$$+D_N\cdot\left[\frac{\partial^2[N]}{\partial x^2}+\frac{\partial^2[N]}{\partial y^2}\right]+\frac{k_x}{\theta}\cdot\left[\frac{\partial}{\partial x}\cdot\left([N]\cdot\cancel{\frac{\partial H}{\partial x}}\right)\right]+\frac{k_y}{\theta}\cdot\left[\frac{\partial}{\partial y}\cdot\left([N]\cdot\cancel{\frac{\partial H}{\partial y}}+[N]\cdot\frac{\partial c}{\partial y}\right)\right]$$

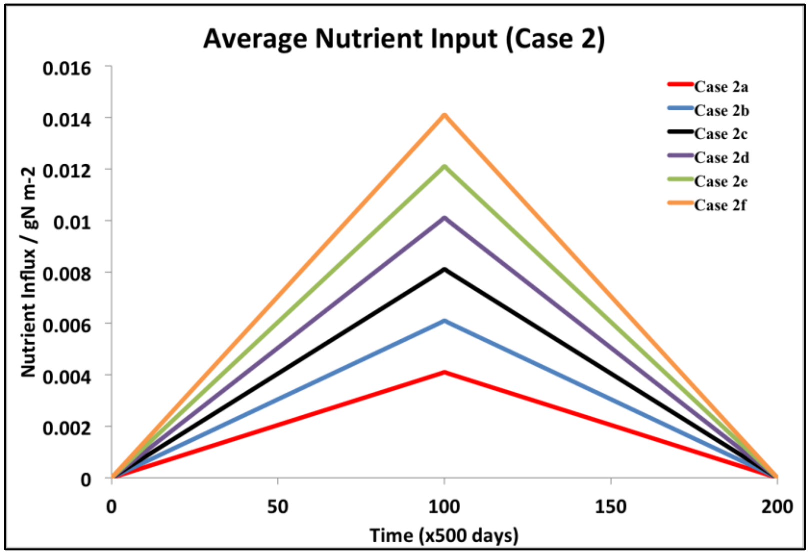
Constant Nutrient Inputs

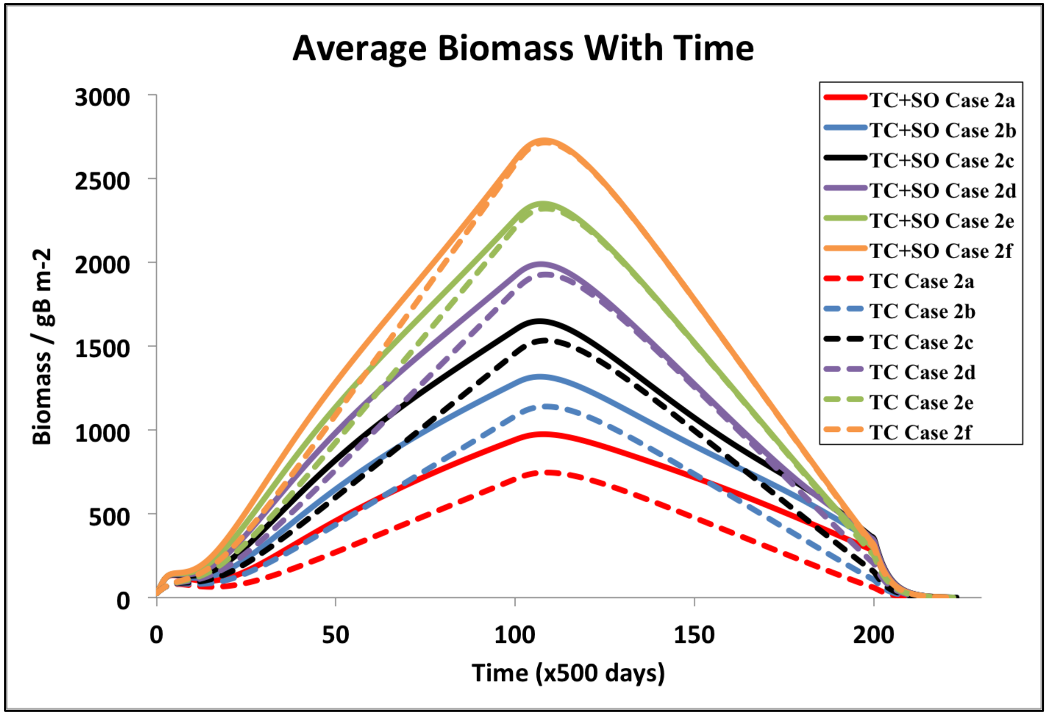


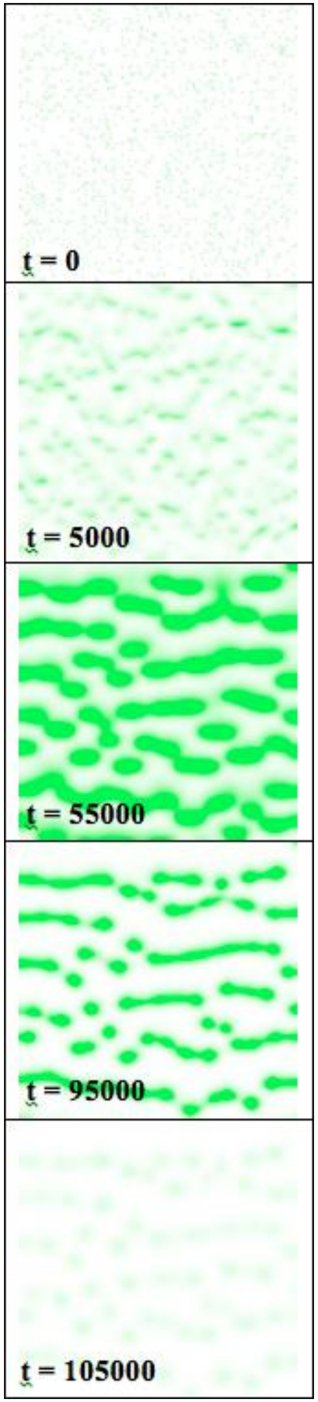




Transient Nutrient Inputs

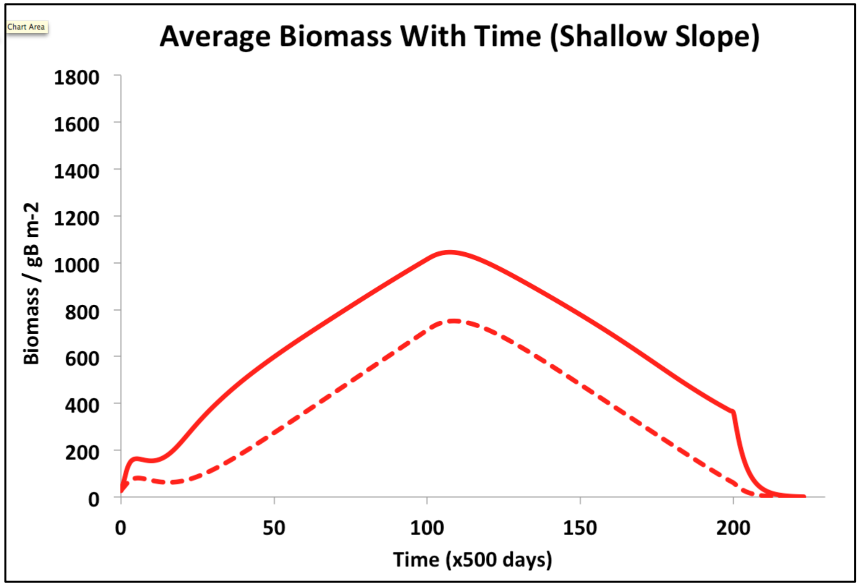


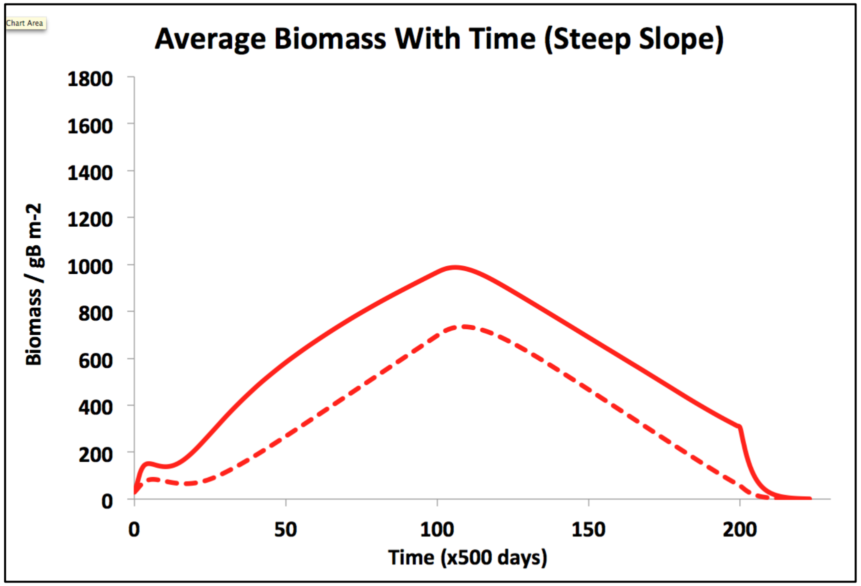




Putting it together: Effects of slope and nutrient inputs on biomass growth

Reducing the nutrient limitation yields greater topographic control





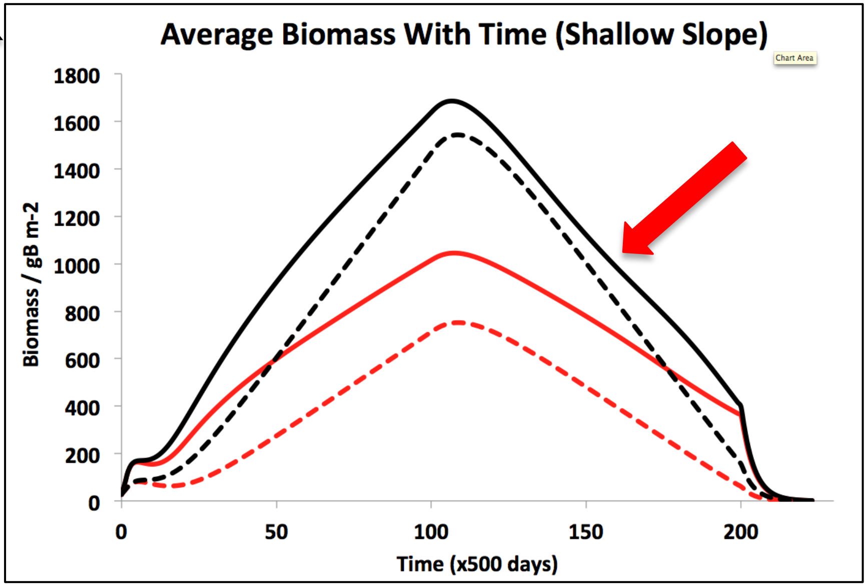
shallower slopes yield greater self-organizing control

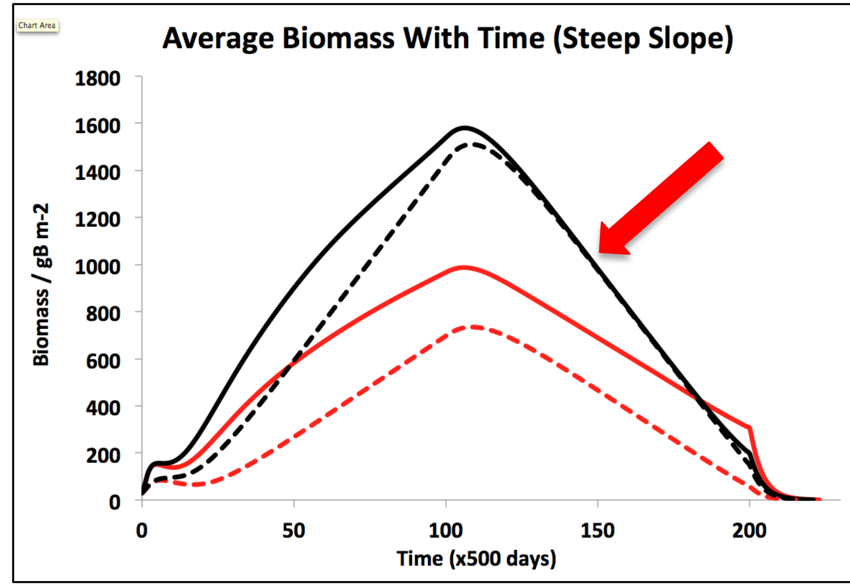
steeper slopes yield greater topographic control

1) Accumulation of biomass is always greater when both topographic and self-organizing processes are accounted for

Putting it together: Effects of slope and nutrient inputs on biomass growth

Reducing the nutrient limitation yields greater topographic control





shallower slopes yield greater self-organizing control

steeper slopes yield greater topographic control

1) Accumulation of biomass is always greater when both topographic and self-organizing processes are accounted for
2) As nutrient availability is increased, topography increasingly exerts it's control. As nutrient availability is reduced, self-organizing processes increasingly exert their control

Implications of findings on the simulation of wetland dynamics

(1) TC+SO models yield higher net primary productivity (NPP) than TC only models. While TC only models can be calibrated to match the observed NPP at present, during prediction, the simulated NPP can still become biased.

(2) High nutrient and/or topographic gradients lead to spatially-uniform vegetation dynamics. Results suggest that TC only models may sufficiently represent growth dynamics of peatlands with:

- high nutrient inputs and/or are located on
- terrains with relatively high topographic gradients (note: 0 - 0.03 m m^{-1} observed for northern peatlands [*Belyea*, 2007]).

(3) Transient simulations are more suitable for predicting system trajectory under chronic perturbations. In the northern bogs, chronic N deposition has been identified as a perturbation to the ecosystems [*Galloway*, 2004]. Memory of the system needs to be taken into consideration when studying how N addition will affect system productivity and dynamics in the future.

Acknowledgement

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