River ecomorphodynamics and bioengineering

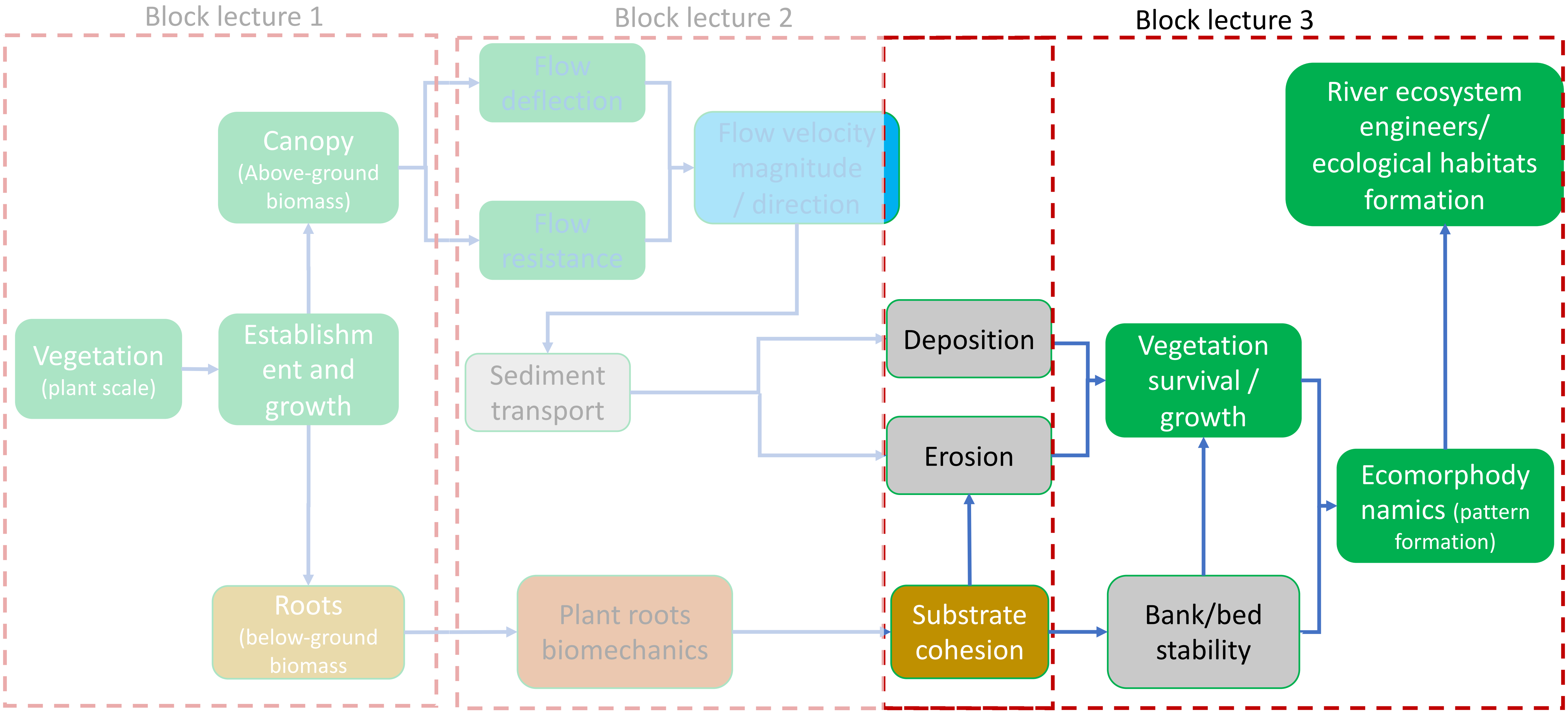
(ENV-418, A.Y. 2025-26)

4ETCS, Master option

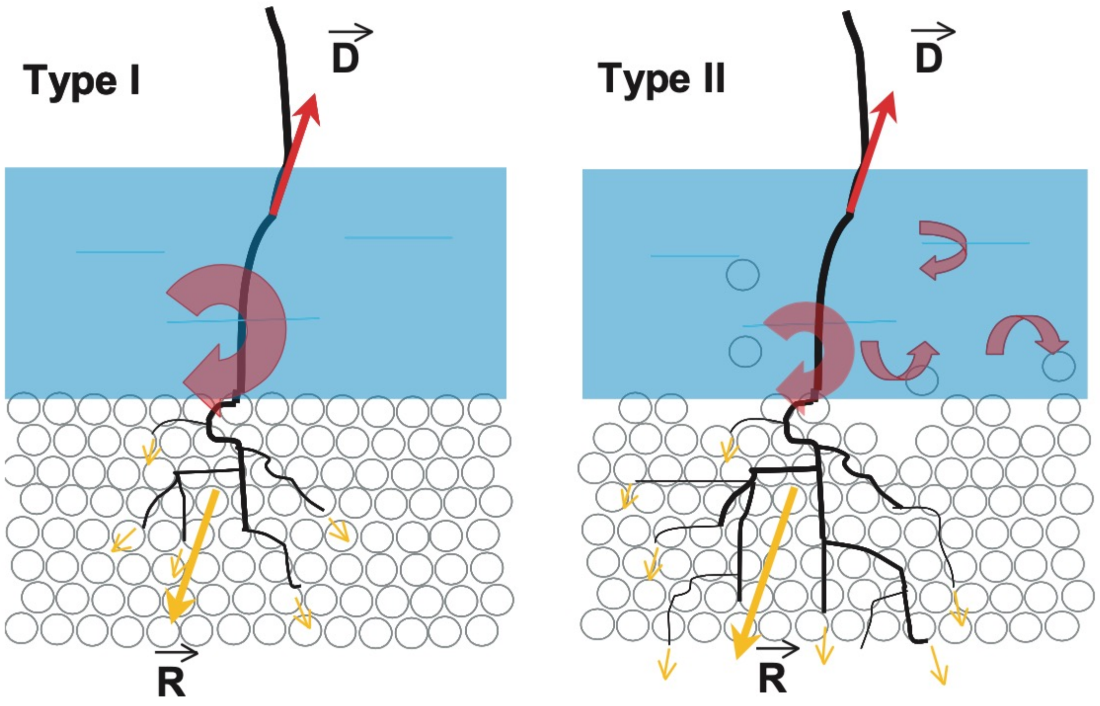
Prof. Paolo Perona
Platform of Hydraulic Constructions

Lecture 12-3: Vegetation uprooting and patterns formation

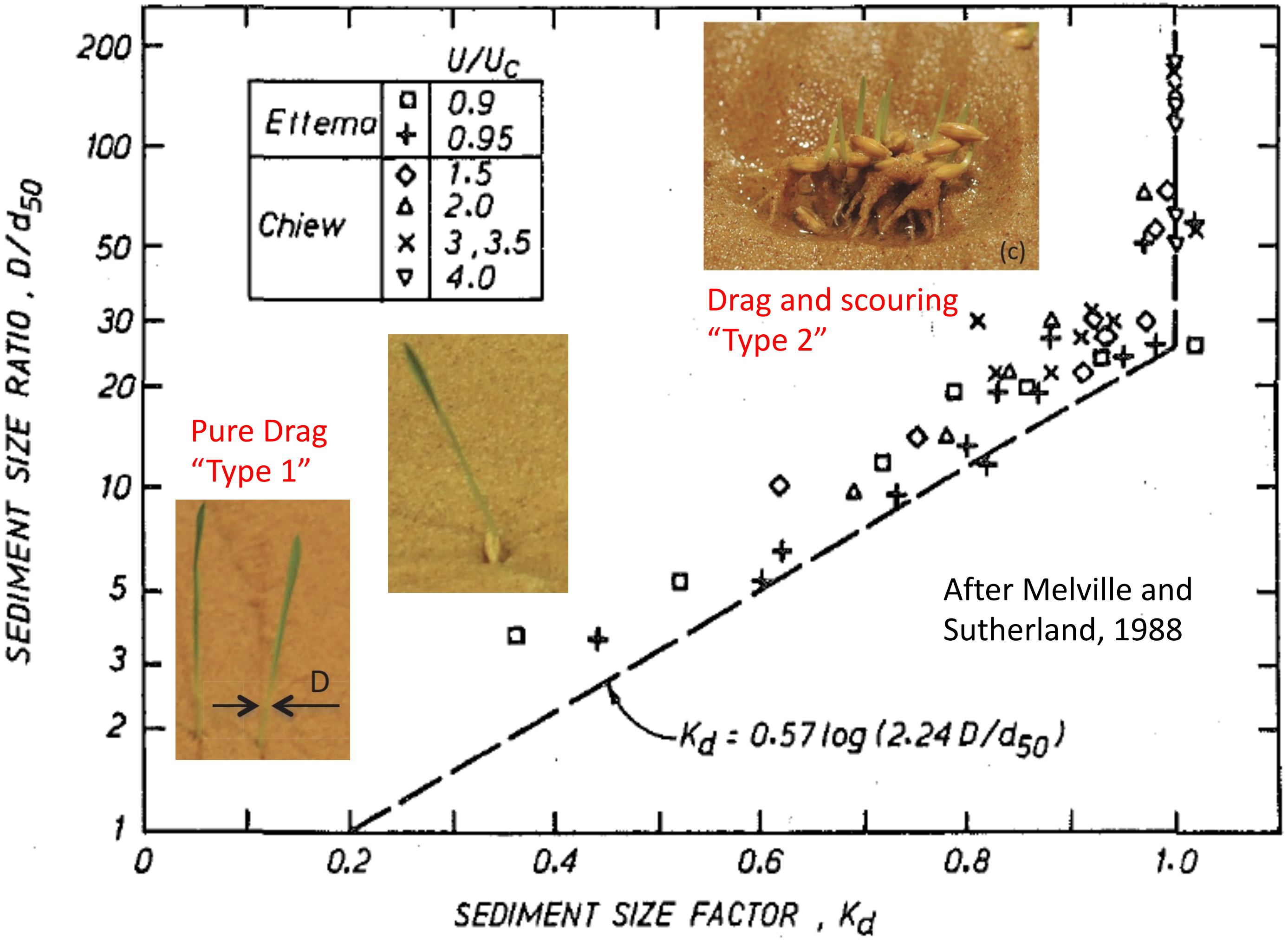
Salicacee and fluvial processes



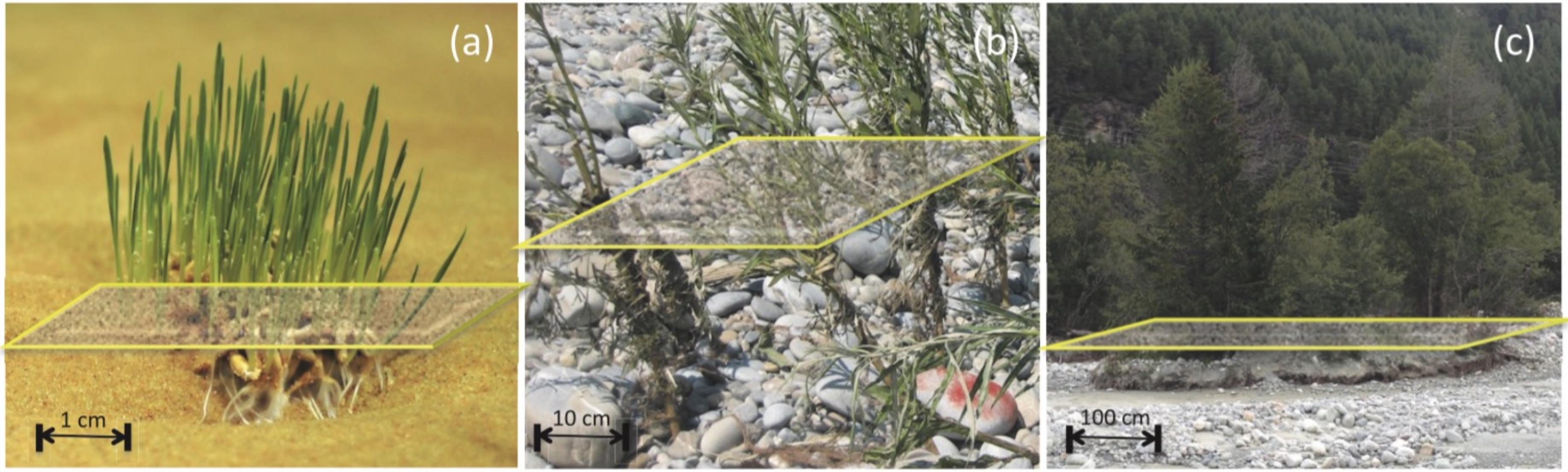
Type of vegetation uprooting by flow

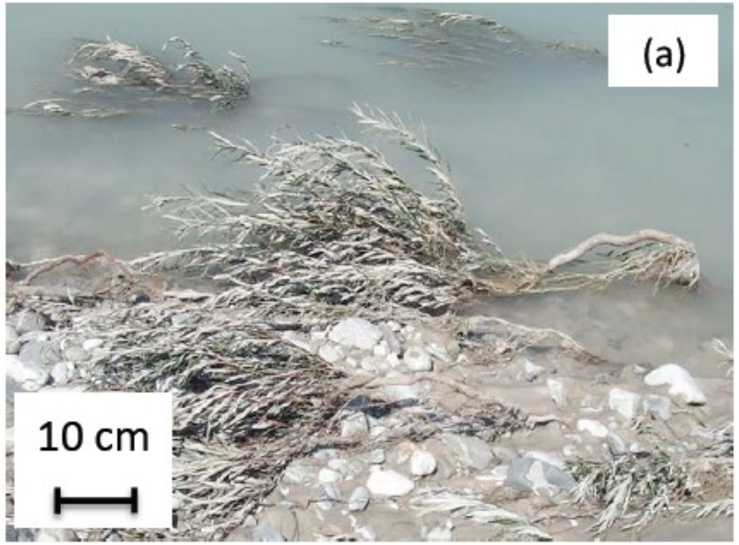


Edmaier et al., HESS, 2011

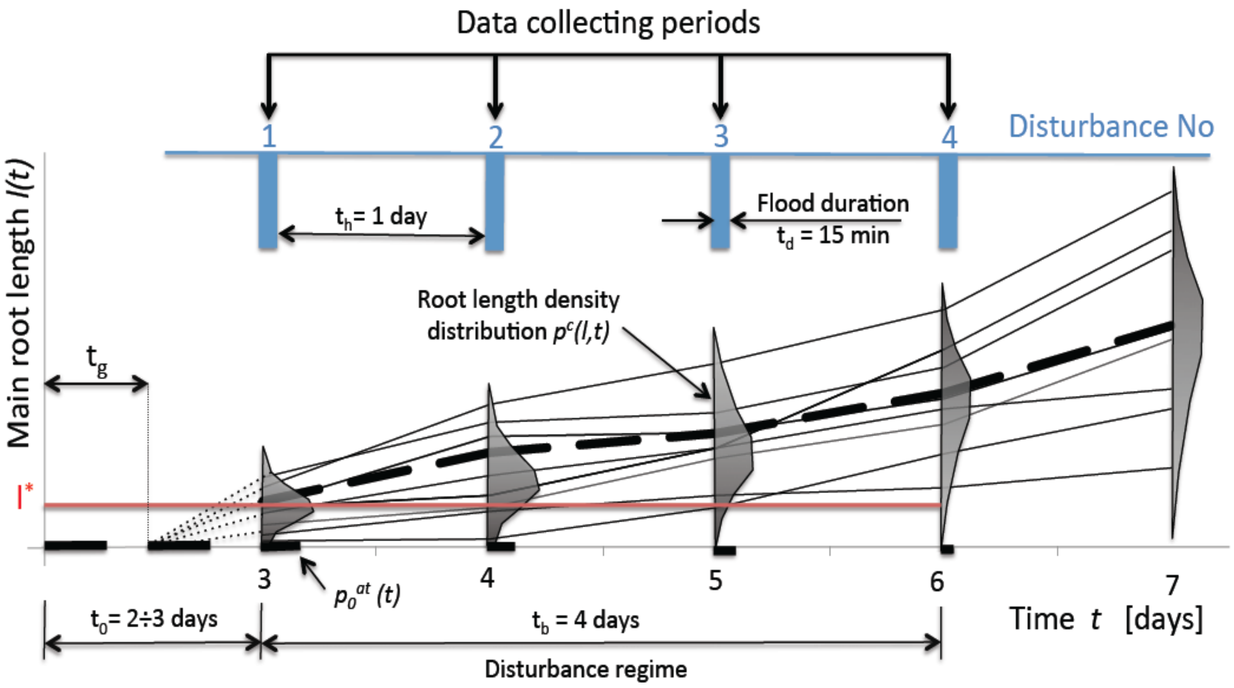


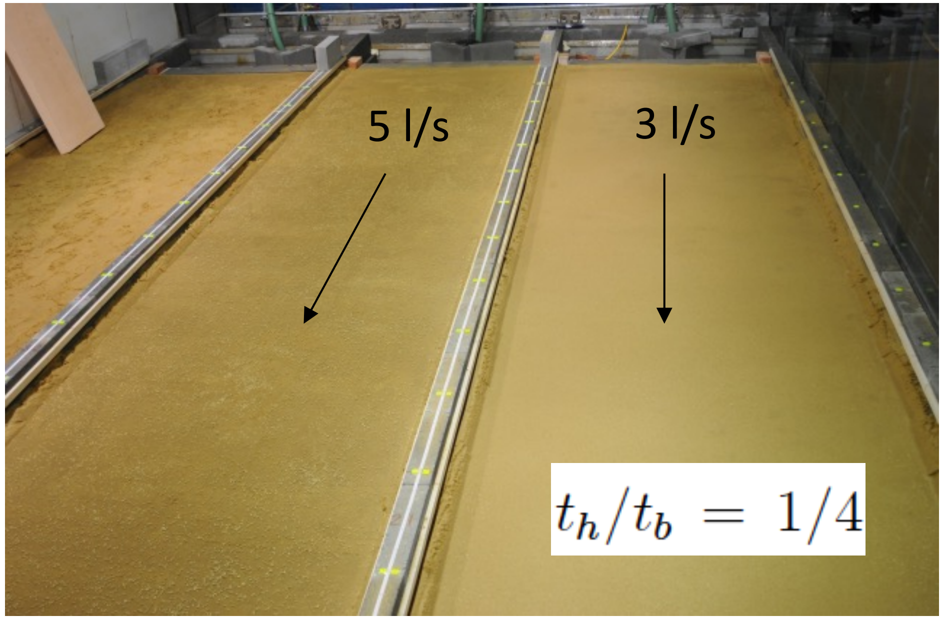
Field observations





Unravelling uprooting Type 1





(Perona et al., Adw. Wat Res, Part 1, 2012)

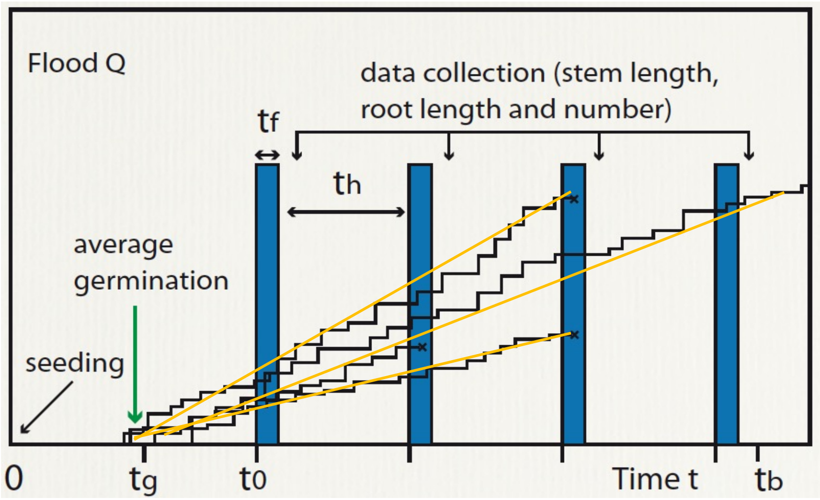
- t_d hydraulic time scale (short)
- t_h hydrological time scale (medium)
- t_b biological time scale (long)

$\frac{t_h}{t_b}$:

<< 1	no colonization (bare)
< 1	competition (patterns)
>= 1	no uprooting (all vegetated)

t_d/t_h; t_d/t_h<<1 → Noise

Uprooting type I: stochastic modelling



$$\frac{\partial p^c(l,t)}{\partial t} = -\frac{\partial}{\partial l}\left[\alpha(l)p^c(l,t)\right] - p^c(l,t)\epsilon(l,t), \qquad \epsilon(l,t) = F(t)G(l)$$

$$G(l) = \frac{1}{t_d} p_{\text{uprooting}}(l)$$

$$F(t) = \begin{cases} 1 & t - t_0 \in [(n-1)(t_h + t_d), n(t_h + t_d) - t_h] \\ 0 & \text{else.} \end{cases}$$

$$p^c(l, t_g) = \delta(l)$$ B.C. $$p_{\text{uprooting}}(l) = \int_0^D p_l(x)dx.$$

$$p^c_{ge}(l,t) = \int_0^t p^c(l,t)p_{ge}(t_g)dt_g$$

$$p^c_{ge,gr}(l,t) = \int_0^\infty p^c_{ge}(l,t)p_{gr}(k)dk$$

$$G(l) = \frac{1}{\tau_e} e^{-k_e l}.$$

We use Superstatistics theory (Beck and Cohen, Physica A, 2003) to introduce the stochastic role of both germination time and growing rate

$$p^c_{gr}(l,t) = \frac{1}{t} e^{\frac{t}{\tau_e l k_e}\left(\sum_{n=1}^{n_{max}} e^{-k_e a_n}\left(1-e^{\frac{k_e l t_d}{t}}\right)\right)} \Gamma_{\eta,\theta}\left(\frac{l}{t}\right)$$

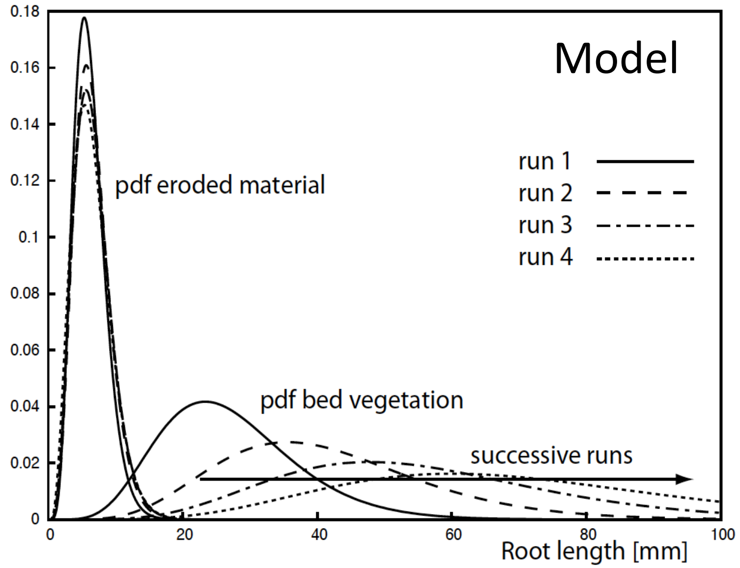
The constancy
be obtained on
decays expone

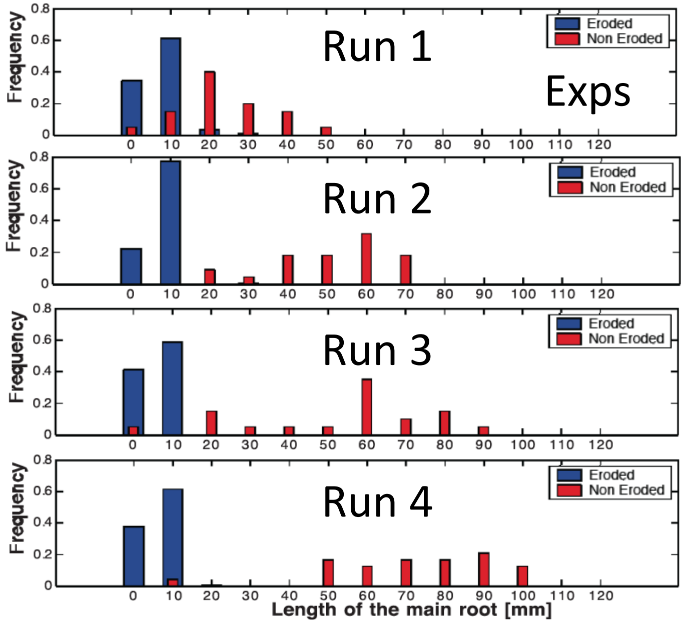
The probability for plant to be uprooted is simply

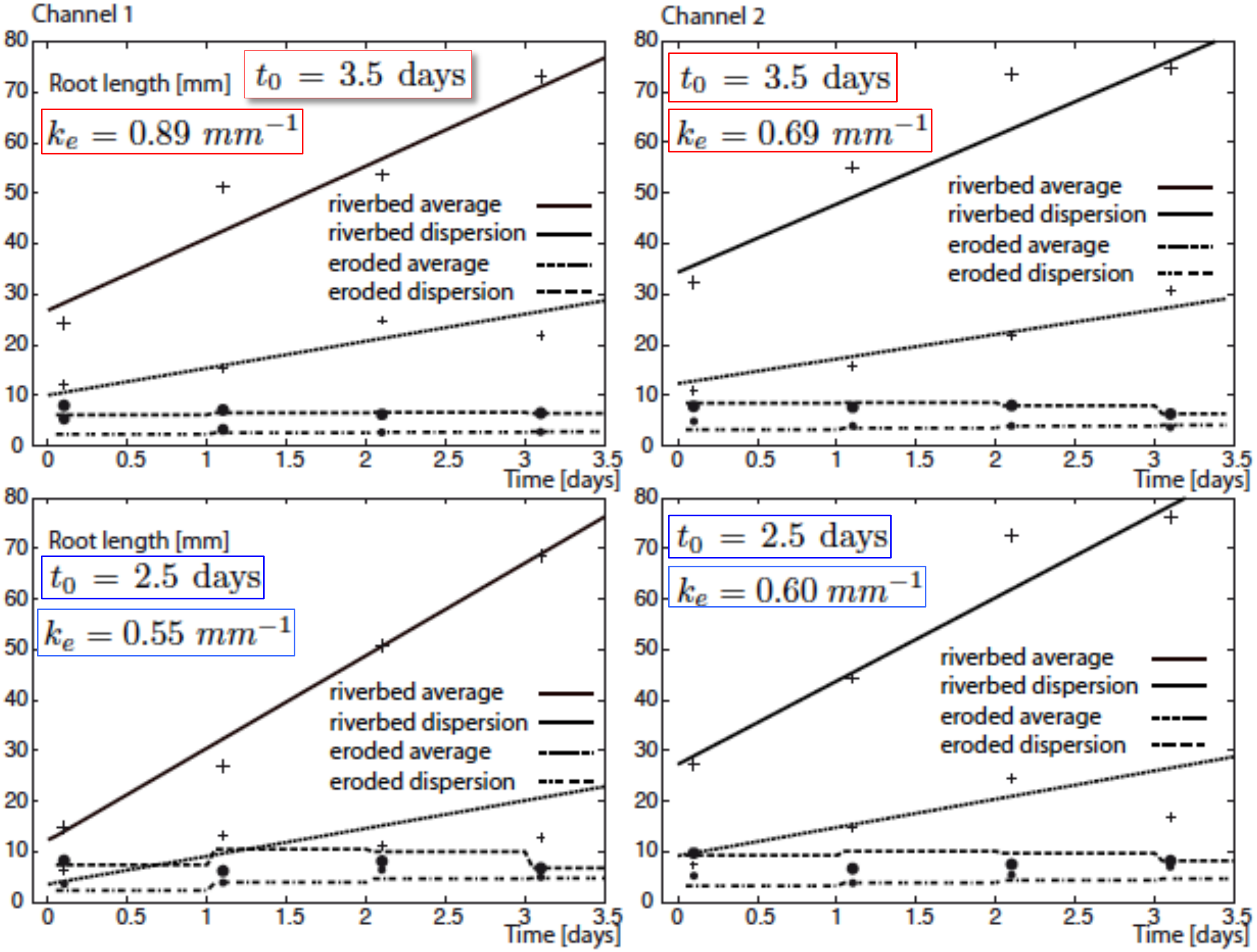
$$q_t(l) = \frac{1}{Norm(t)} p^c_{ge,gr}(l,t)\epsilon(l,t)$$

(Crouzy and Perona, Adw. Wat Res, Part 2, 2012)

Crouzy and Perona, Adv. Wat Res, 2012

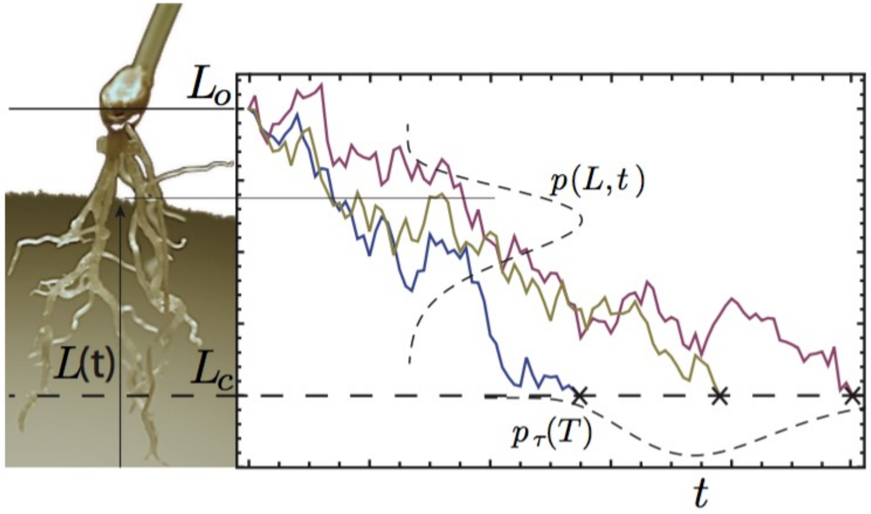






Uprooting Type II: stochastic modelling and resilience to uprooting

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES



$$\frac{dL}{dt} = -v_{sed}(L,t) + g(L,t)\xi(t), \qquad t > 0$$

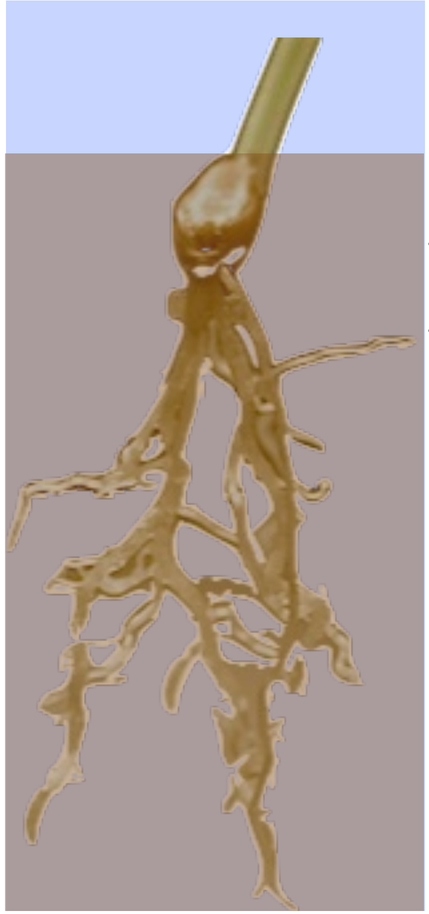
$$\frac{\partial p}{\partial t} = v_{sed}(t)\frac{\partial p}{\partial L} + \frac{1}{2}g(t)\frac{\partial^2 p}{\partial L^2}, \qquad L > L_c.$$

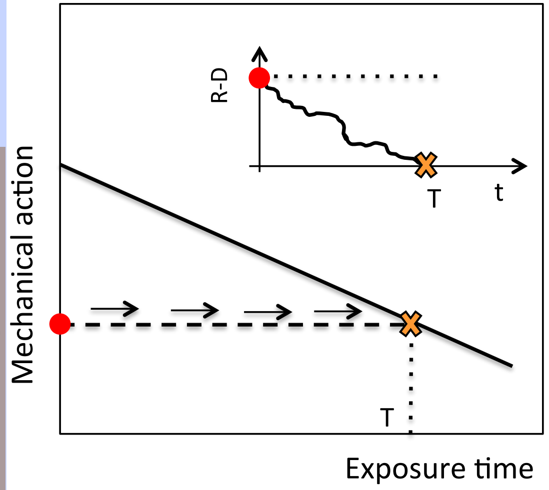
$$p(L_0, 0) = \delta(L - L_0)$$

$$p(L,t) = 0 \text{ for } L \to +\infty.$$

$$p(L,t) = \frac{1}{\sqrt{4\pi G(t)}}\left(e^{\frac{-(L+V(t)-L_0)^2}{4G(t)}} - e^{\frac{V(t)(L_0-L_c)}{G(t)} - \frac{(L+V(t)-2L_c+L_0)^2}{4G(t)}}\right)$$

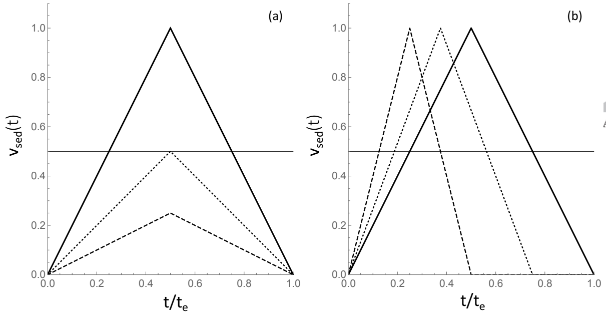
$$p_\tau(T) = \frac{L_e e^{\frac{-(L_e-V(T))^2}{4G(T)}}\left(\frac{g(T)}{2} + e^{\frac{(L_e+V(T))^2}{4G(T)}} W(T)\right)}{2\sqrt{\pi}G(T)^{3/2}}$$





Perona and Crouzy, PRSLA, 2018

Probability of scouring and time to uprooting



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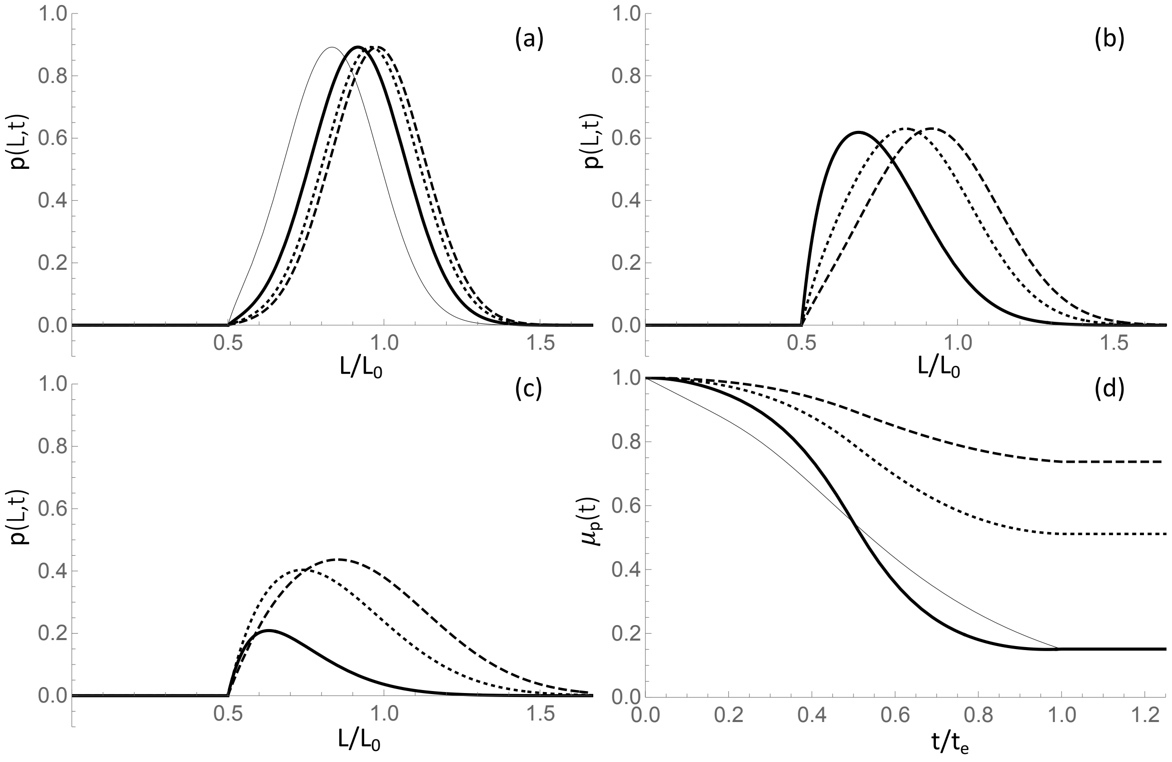


Figure 4. Time dependent evolution of the pdfs, $p(L,t)$ (a-c), and their mean (d) for the erosion processes shown in Figures 3a where $L_0 = 3$ and $L_c = 1.5$. Line thickness and type correspond to the adopted erosion functions. a) t/t_e=0.25; b) t/t_e=0.5; c) t/t_e=1

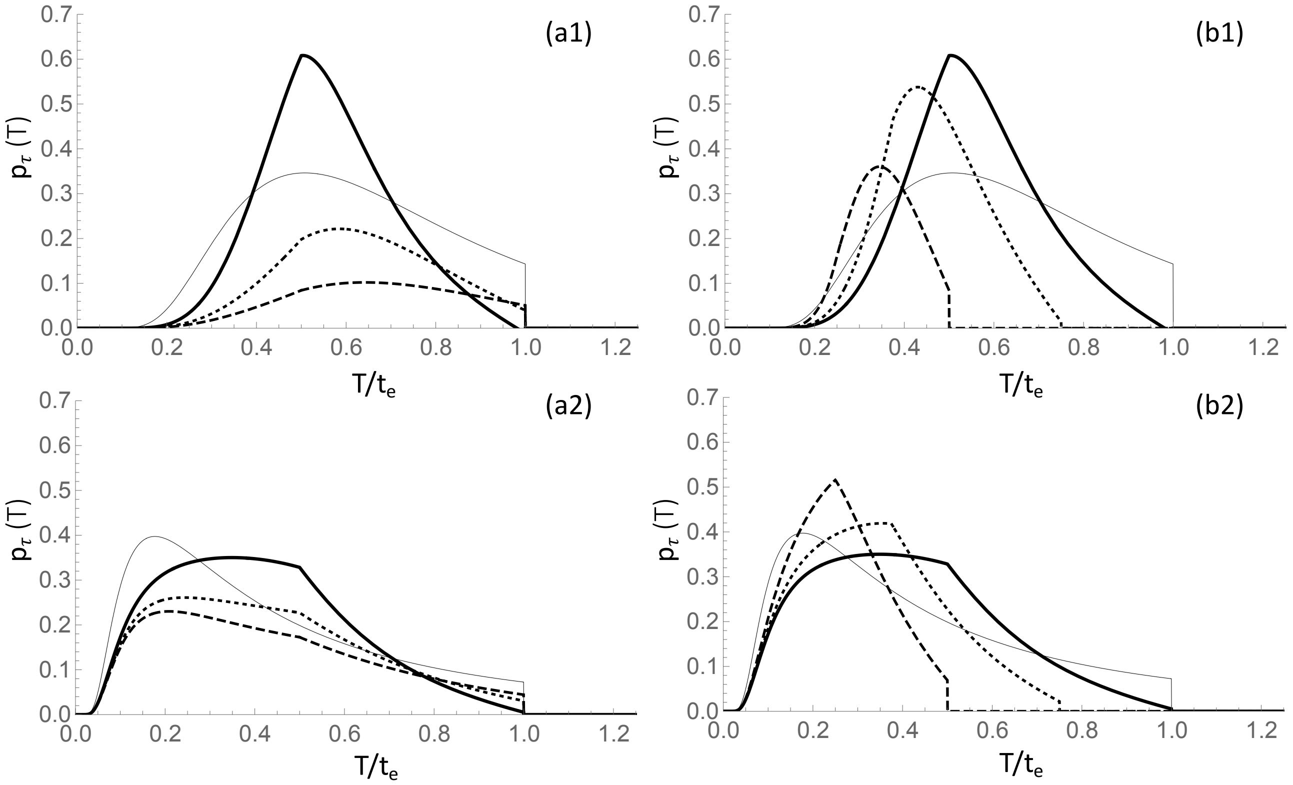


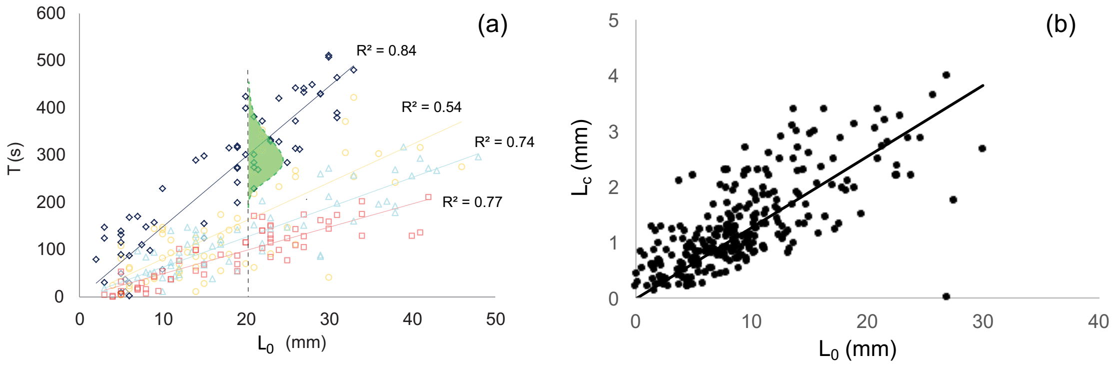
Figure 7. Probability density functions of time-to-uprooting, $p_\tau(T)$ for the erosion processes shown in Figure 3a,b for different magnitude of process variance: a1,b1) g=0.1; a2,b2) g=0.5

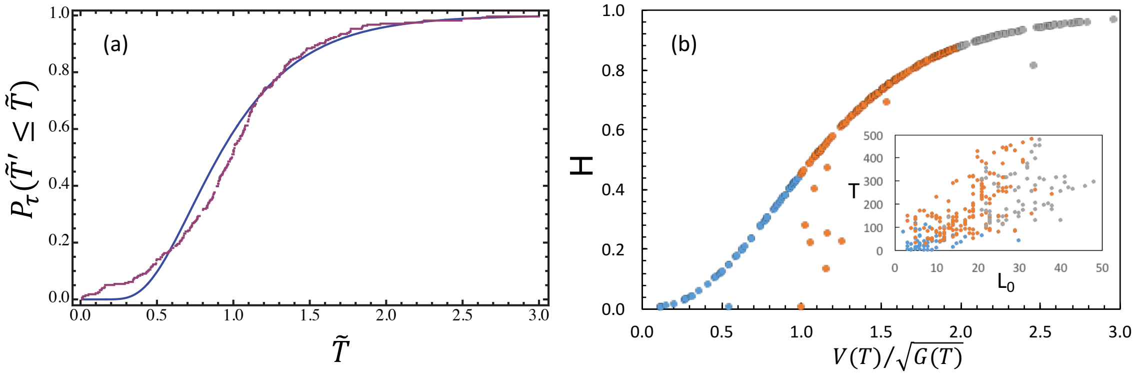
Case of constant erosion rate and noise variance

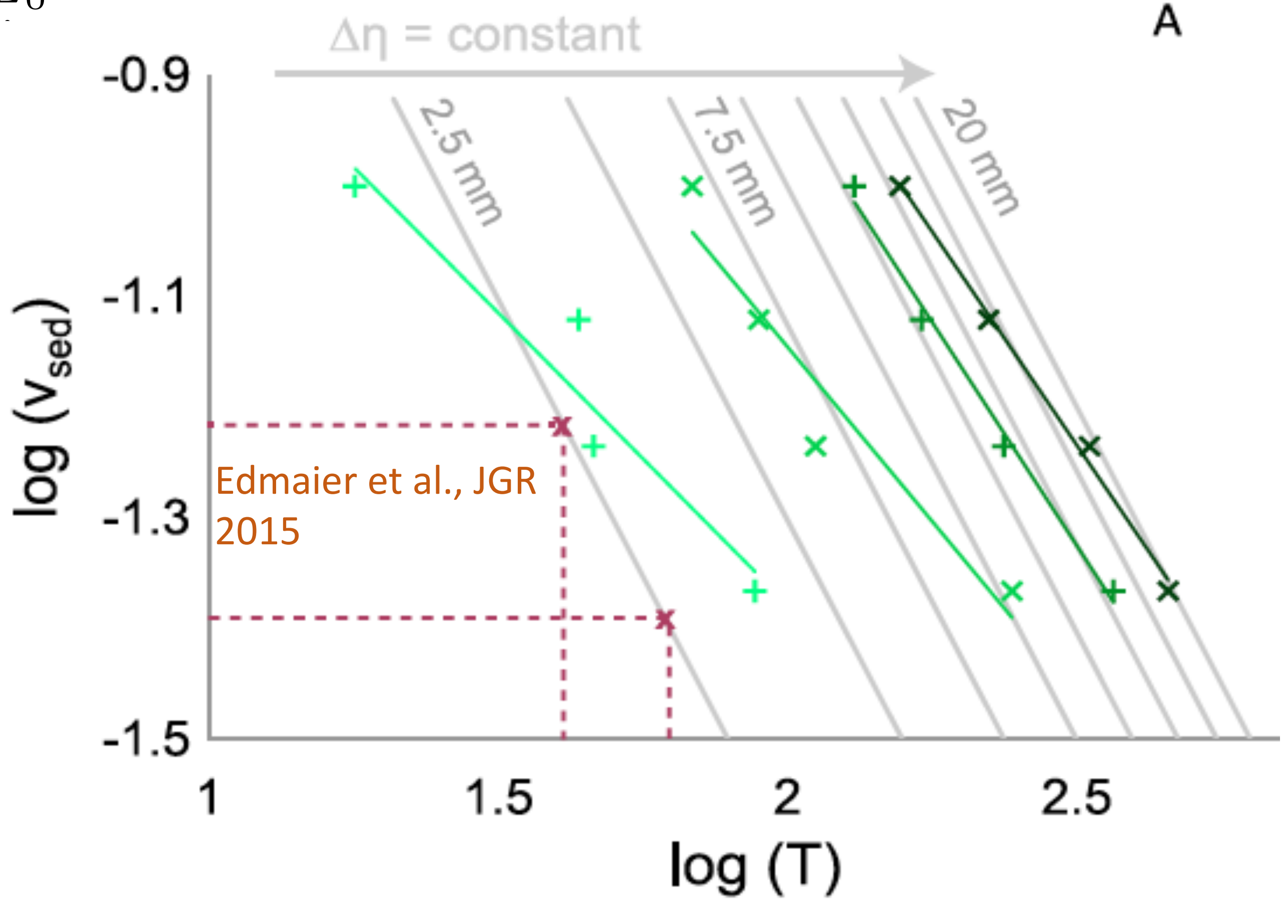
$$p_{\mathcal{T}}(\tilde{T}) = \frac{e^{-\frac{(1-\tilde{T})^2}{2\tilde{\sigma}^2\tilde{T}}}}{\sqrt{2\pi\tilde{T}^3}\tilde{\sigma}},$$

$$\tilde{T} = \frac{Tv_{sed}}{L_0} \qquad \tilde{L} = \frac{L}{L_0}$$

$$\tilde{\sigma}^2 = \frac{\sigma^2}{L_0 v_{sed}}$$







Because of drag, critical scouring is less than rooting depth!!

Bank erosion

Bank erosion rate (Partheniades, 1965), with k_d and a parameters (usually taken as constant)

$$\varepsilon = k_\mathrm{d}(\tau - \tau_\mathrm{c})^a$$

Soil reinforcement by roots (extended Mohr-Coulomb)

$$\tau = c' + (\sigma - u_\mathrm{a})\tan\phi' + (u_\mathrm{a} - u_\mathrm{w})\tan\phi^\mathrm{b} + S_\mathrm{r}$$

(e.g., Waldron 1977; Wu et al., 1979; Waldron and Dakessian 1981, Pollen and Simon, 2005; Docker and Hubble,
2008)

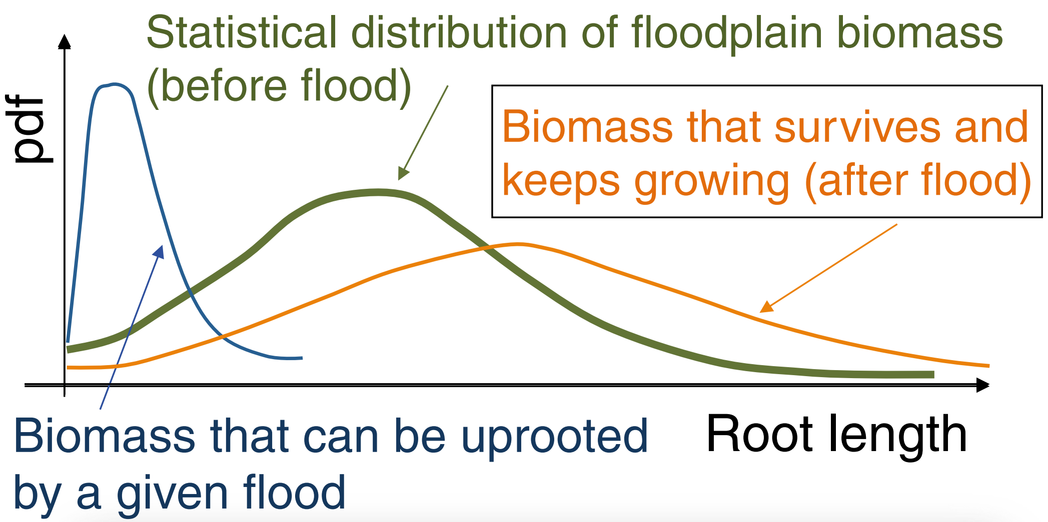
Effect of roots on critical shear stress (e.g., Paola, 2001)

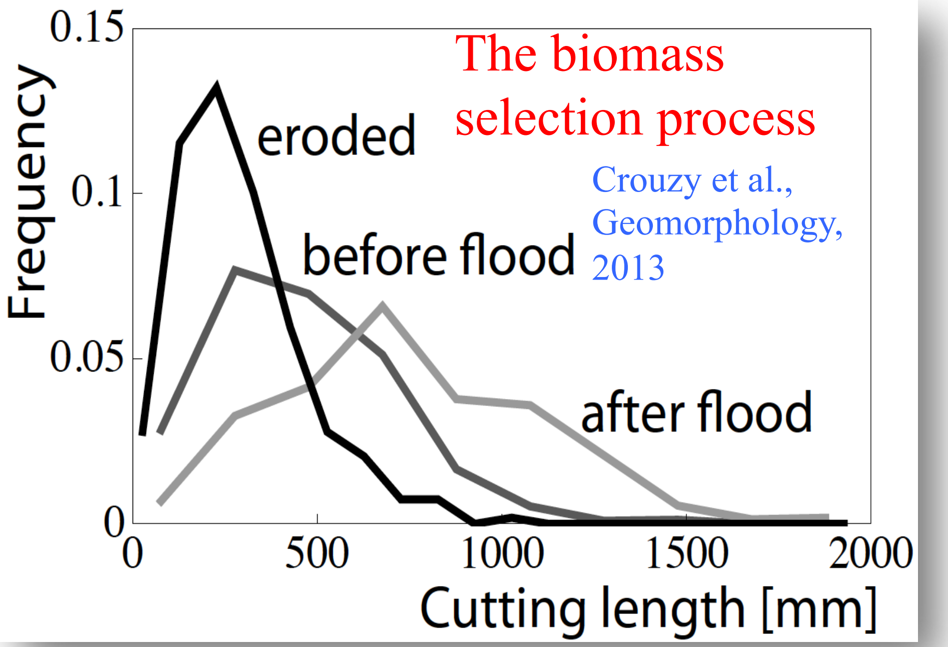
$$\tau_c = \tau_{c,0}(1 + \sigma_1 \rho),$$

Vegetation selection process and recruitment

Biomass selection by floods

Thur flood

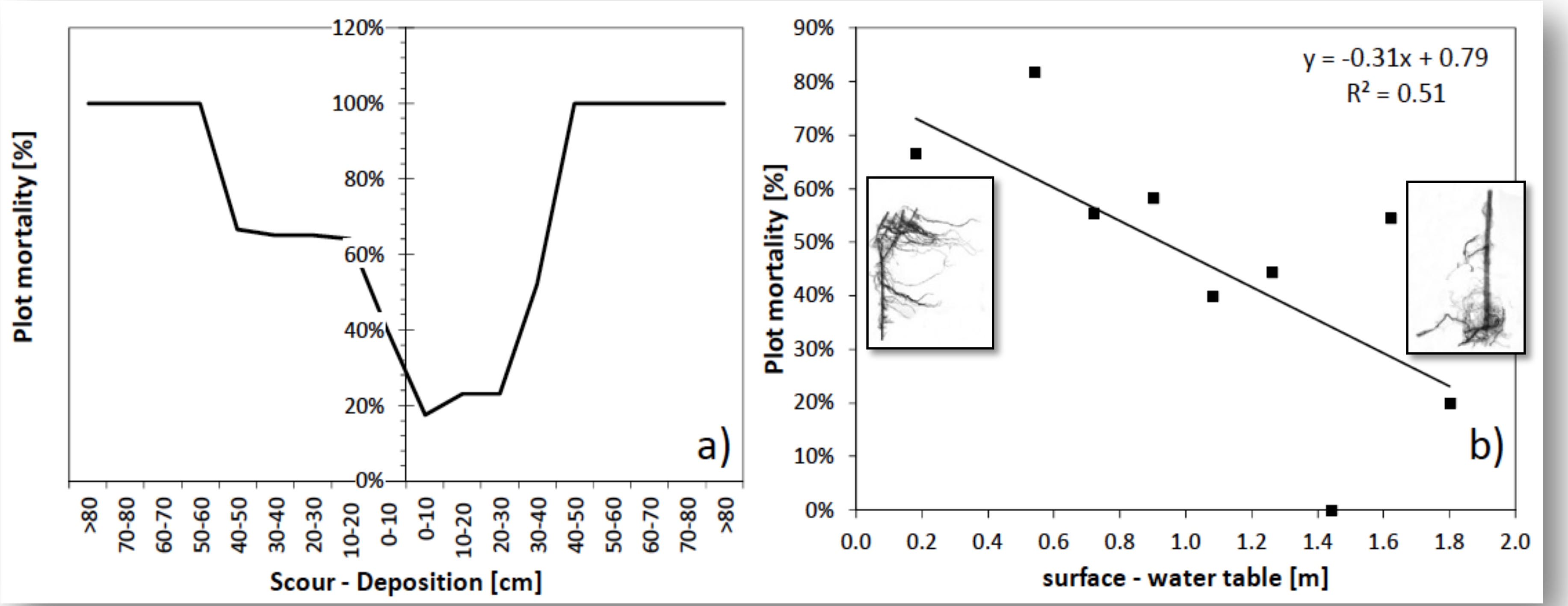




The role of soil topography

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

Pasquale et al., Hydrol. Proc., 2014

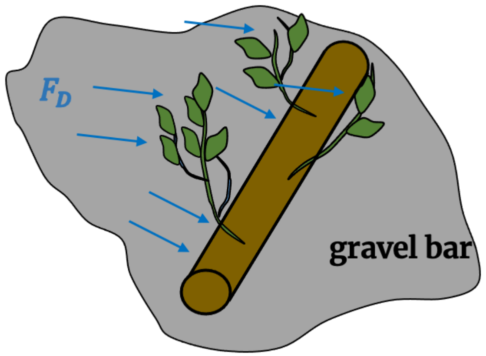


- Deposition of sediment has a protective effect only up to a certain amount of deposit;
- The mortality curve is asymmetric
- Surface roots contribute more to sediment stabilization, but when that layer is removed the plant is uprooted;
- Deeper roots contribute less to sediment stabilisation, but increase the return time of uprooting events

Wood logs survival and resprouting

Bau et al, JGR 2019

Woodlogs may resprout and survive according to opportunity windows



$$\mathbf{F_{d,n}} + \mathbf{F_{d,t}} + \mathbf{F_n} = \mathbf{R}(L_r),$$

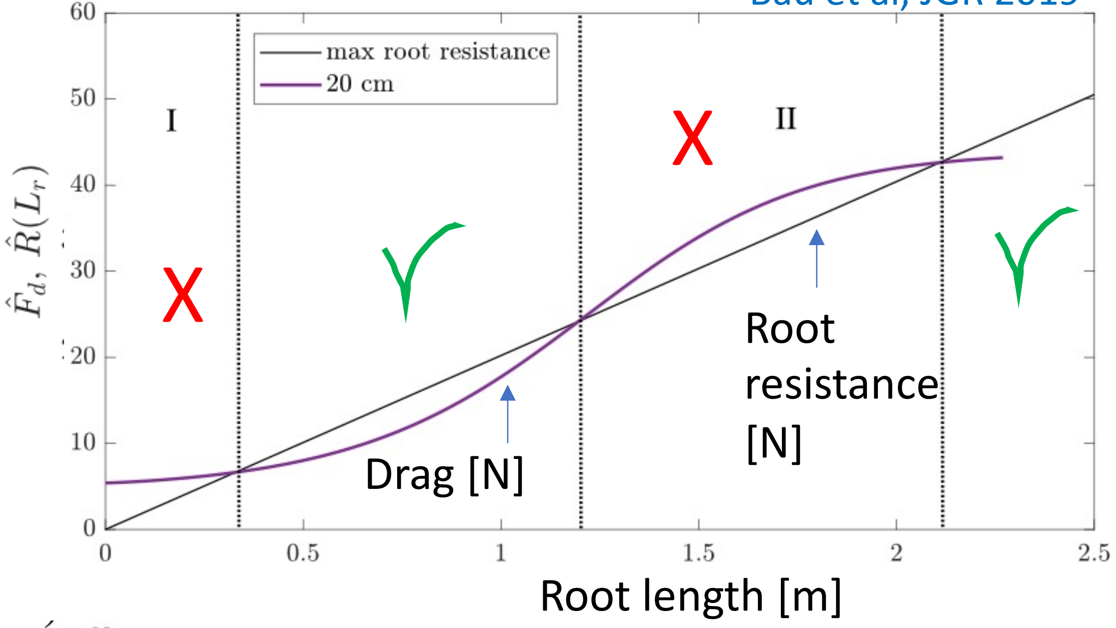
If $R=F_{max}$

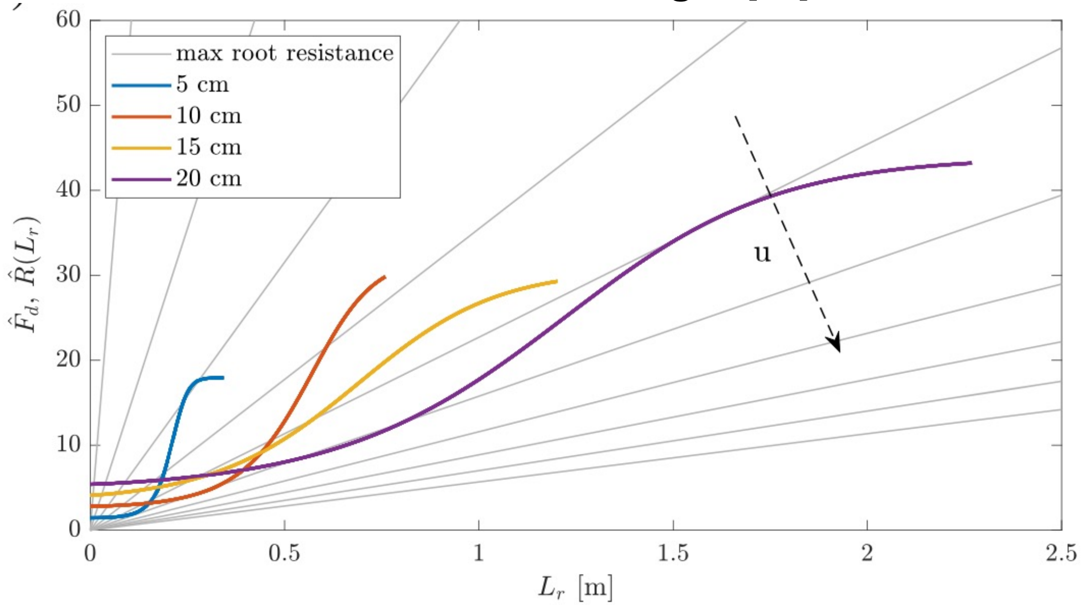
$$\mathbf{F_{d,n}} + \mathbf{F_{d,t}} + \mathbf{F_n} = \mathbf{F_{max}}(L_r),$$

$$F_d = \frac{1}{2} C_d \rho_w u^2 \frac{L\bar{d}}{2} + \frac{1}{2} C_f \rho_w u^2 \left[\pi d_s \left(\frac{\bar{L}_{s,\,max}}{1+e^{\left[-b\left(\left(\frac{L_r}{c_1}\right)^{\frac{1}{d_1}} - t_0\right)\right]}}\right) + \frac{d_L d_l}{2} c_4 \left(\frac{\bar{L}_{s,\,max}}{1+e^{\left[-b\left(\left(\frac{L_r}{c_1}\right)^{\frac{1}{d_1}} - t_0\right)\right]}}\right)\right]$$

$F_{max} \propto$ Root length

I. Roots too short compared to drag → uprooting
II. Roots grow and overcome drag → resist
III. Stem leaves grow, drag augment more than root resistance → uprooting
IV. Roots are well developed, drag not sufficient → survival

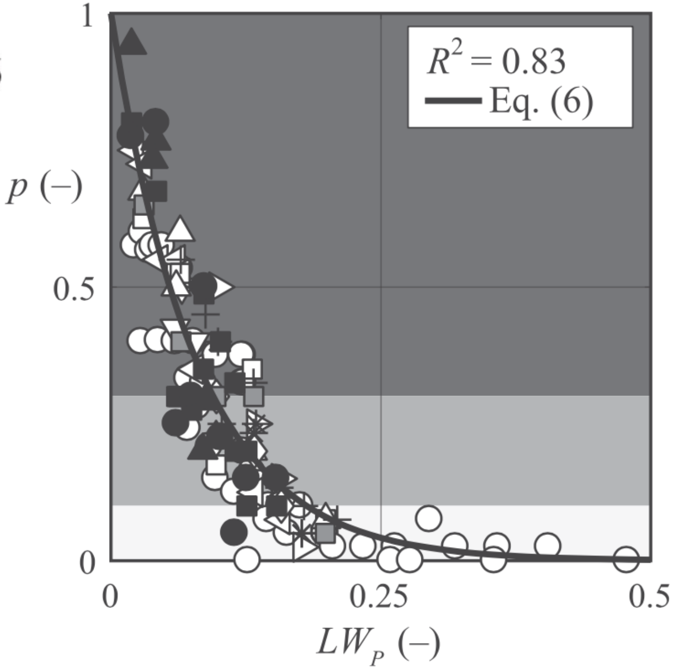




Woodlogs entrainment and transport

Source: Schalko et al. 2019

$$LW_P = x_n \left(\frac{v_o{}^2}{2gL_L} \right)^{0.43} \left(\frac{d_P}{L_L} \right)^{0.6}$$

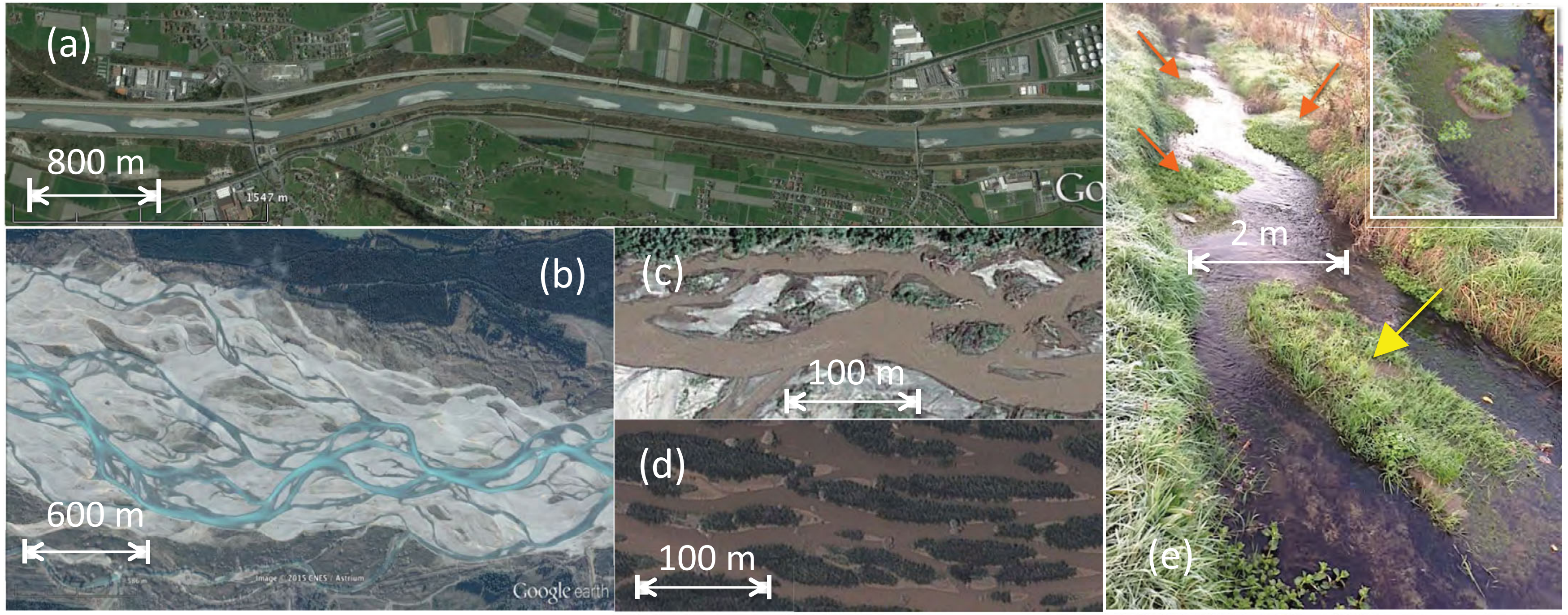


- Large wood is mobilized during large events;
- LW is deposited within secondary channels, on river bars and at bridge piers;
- LW have an effect on river morphodynamics and safety of structures

Ecomorphodynamics: explain nature processes

The morphodynamic tryade

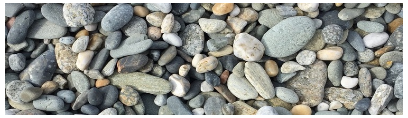
PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES



Study of the planimetric, morphologic, ecologic evolution of riverine environment.

Three key ingredients

Water/air



Sediment

} Morpho-dynamics

Vegetation/biology

} Ecomorphod. / biomorphodynamics

Timescale involved

- hydrodynamic, hydrologic, biologic;

- t_d hydraulic time scale (short)
- t_h hydrological time scale (medium)
- t_b biological time scale (long)

$\frac{t_h}{t_b}$		
	<< 1	no colonization (bare)
	< 1	competition (patterns)
	>= 1	no uprooting (all vegetated)

t_d/t_h; t_d/t_b<<1 → Noise

Perona et al., ESPL, 2014; Baerenbold et al., WRR, 2016
Bertagni et al., PNAS, 2018

Consider for the sake of simplicity just a 1D model

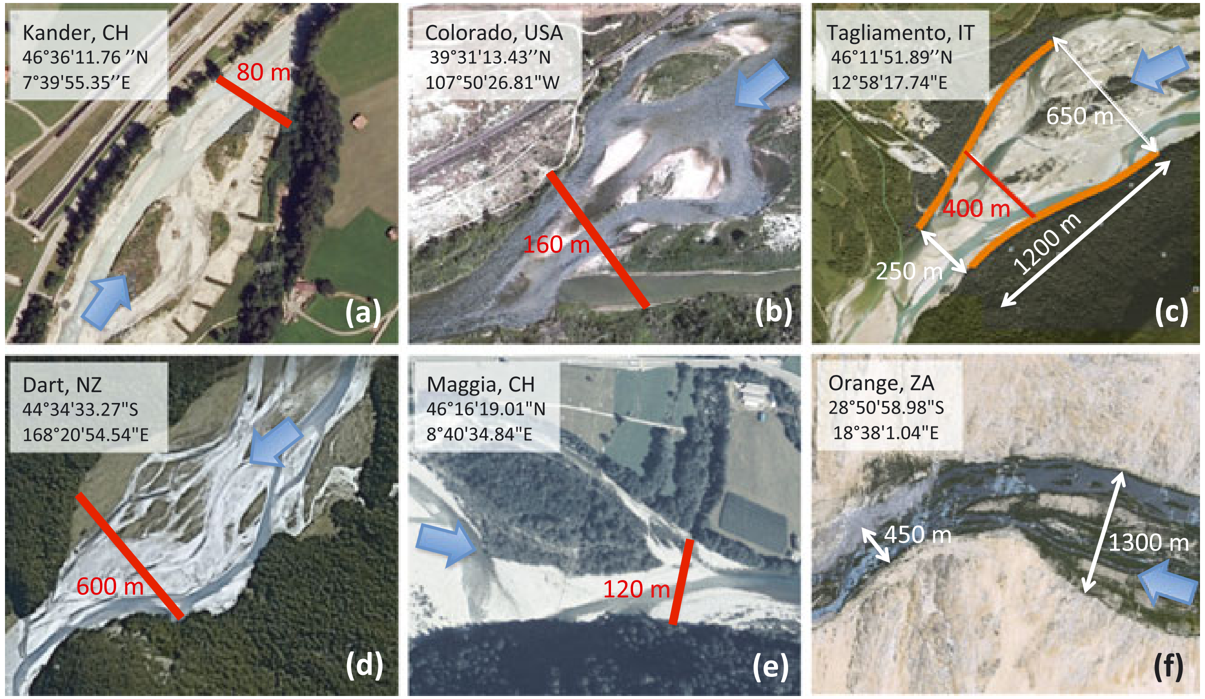
$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\left[\frac{\partial \eta}{\partial x} + \frac{\partial H}{\partial x}\right] + \frac{C_f(\phi)}{H}||\mathbf{U}||U = 0$$

$$\frac{\partial H}{\partial t} + \frac{\partial U H(1 - m_\sigma \phi)}{\partial x} = 0$$

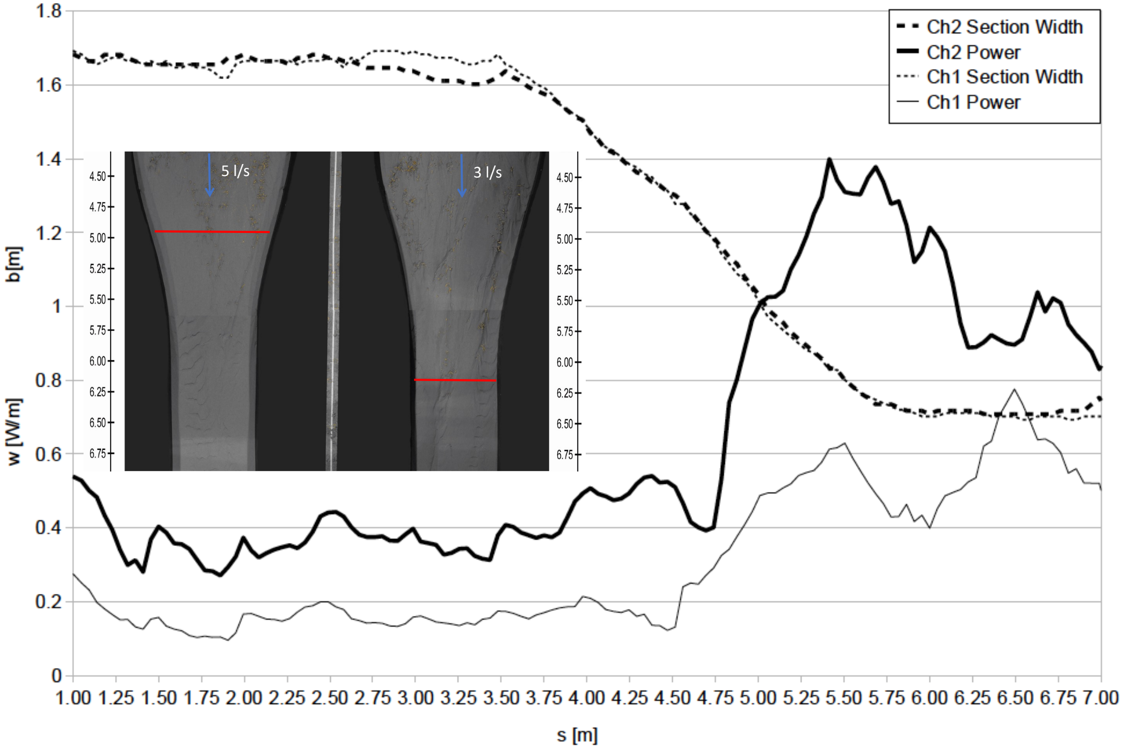
$$(1-\lambda)\frac{\partial \eta}{\partial t} + k\frac{\partial}{\partial s}\left(\frac{U^2}{c^2 G Y^{1/3}} - (\tau_c^* + m_\tau \phi)\right)^{3/2} = 0,$$

$$\frac{\partial \phi}{\partial t} = v_g \phi(1-\phi) + v_D \frac{\partial^2 \phi}{\partial s^2} - \mathrm{f}(\eta, U)\phi$$

1. Vegetated fronts in convectively accelerated streams



After Perona et al., ESPL, 2014



$$\frac{1}{g\Omega}\frac{\partial}{\partial s}(U^2\Omega) + \frac{\partial Y}{\partial s} = i - \frac{Q^2}{\Omega^2 \chi^2 R}$$

$$UbY = Q$$

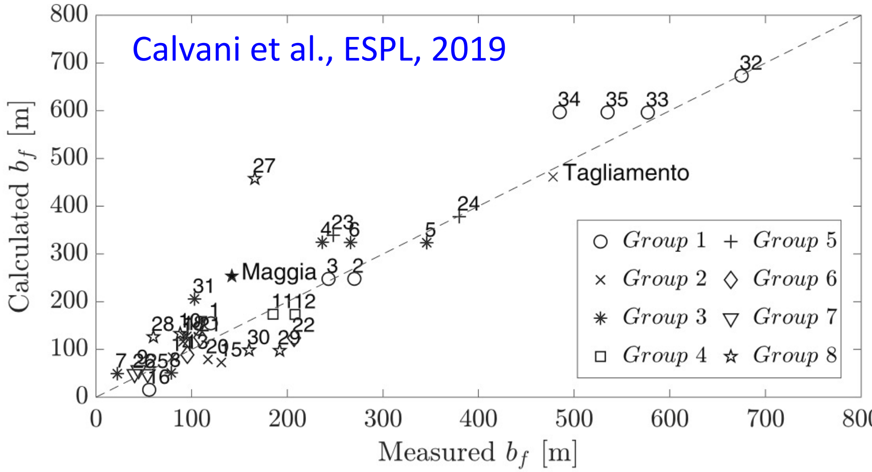
$$\left(\frac{U^2}{\chi_b^2 G} - (\tau_c^* + m\phi)\right)^{3/2} = \frac{Q_s}{kb}$$

$$\phi(\phi_m - \phi) - \beta Y U^2 \phi = 0$$

Steady state

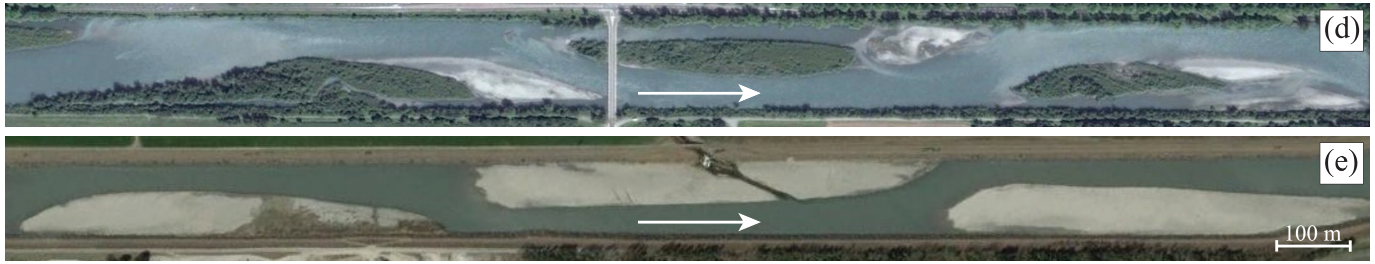
$$b_f = \frac{c^{3/4} G^{3/8} \beta^{7/8}}{\phi_m^{7/8}} \left(\tau_c^* + q_s^{2/3}\right)^{3/8}_{|s=s_f} Q$$

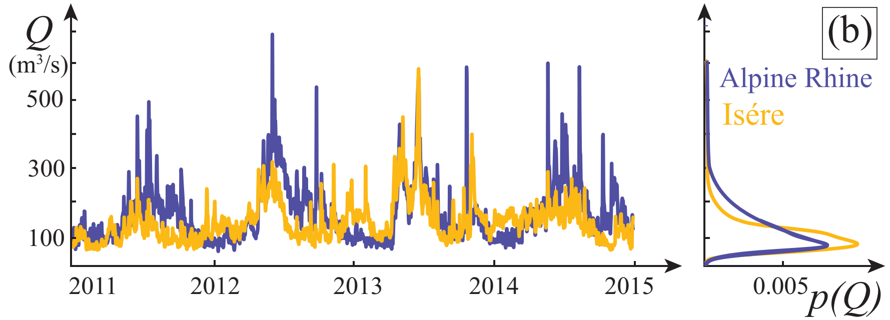
$$b_f = \xi(s_f, Q) Q$$



2. Transition between vegetated and unvegetated stages

Bertagni et al., PNAS, 2018



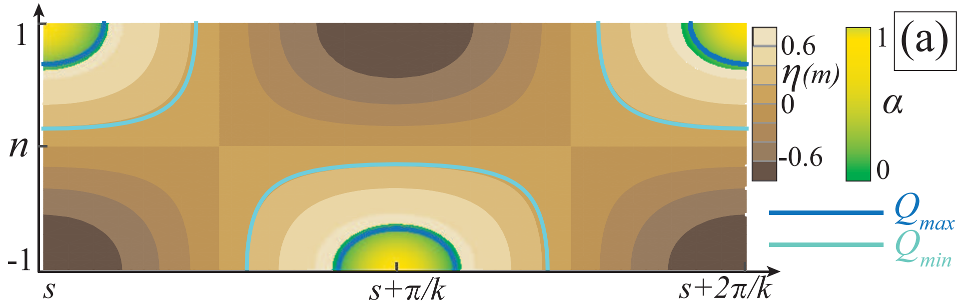


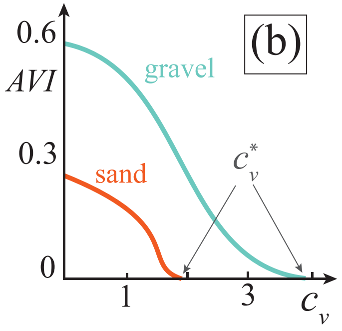
$$\alpha = \frac{1}{T}\int_0^T \left(\nu_g \tilde{K} - \nu_d \theta[\tilde{D}]\, \tilde{D} |\tilde{\mathbf{U}}|^2\right) dt,$$

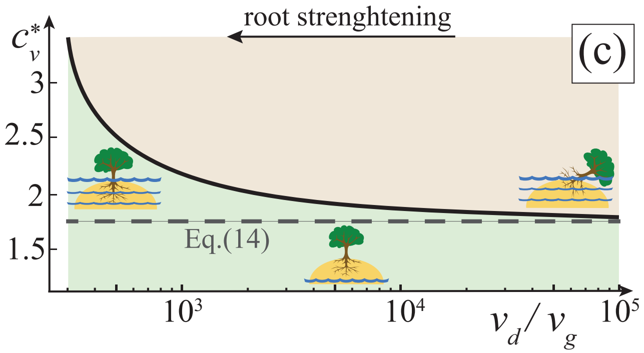
Key parameter controlling the transition

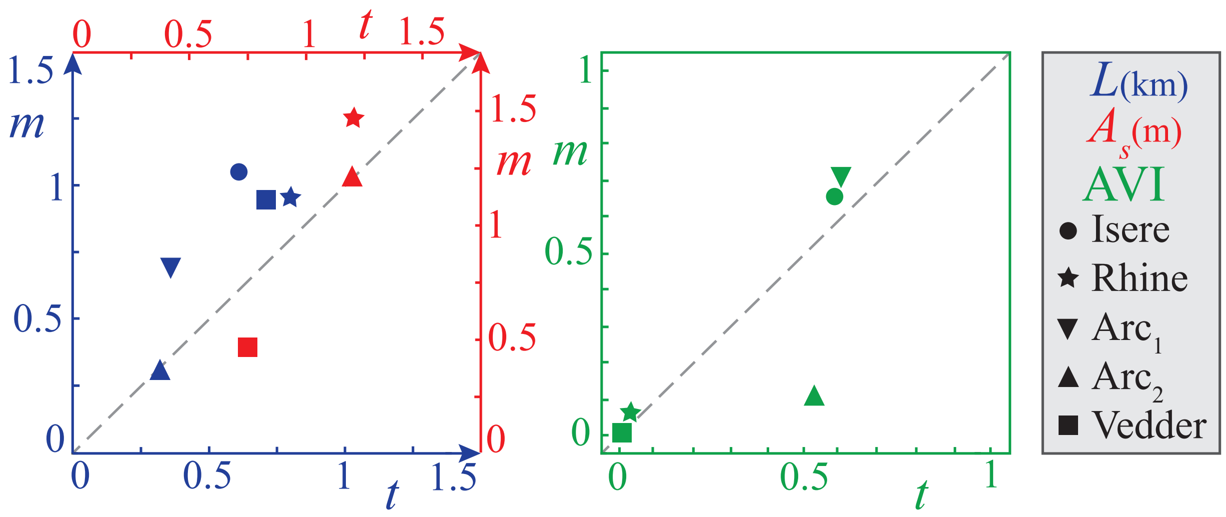
>0 -> vegetated

<0 -> non-vegetated









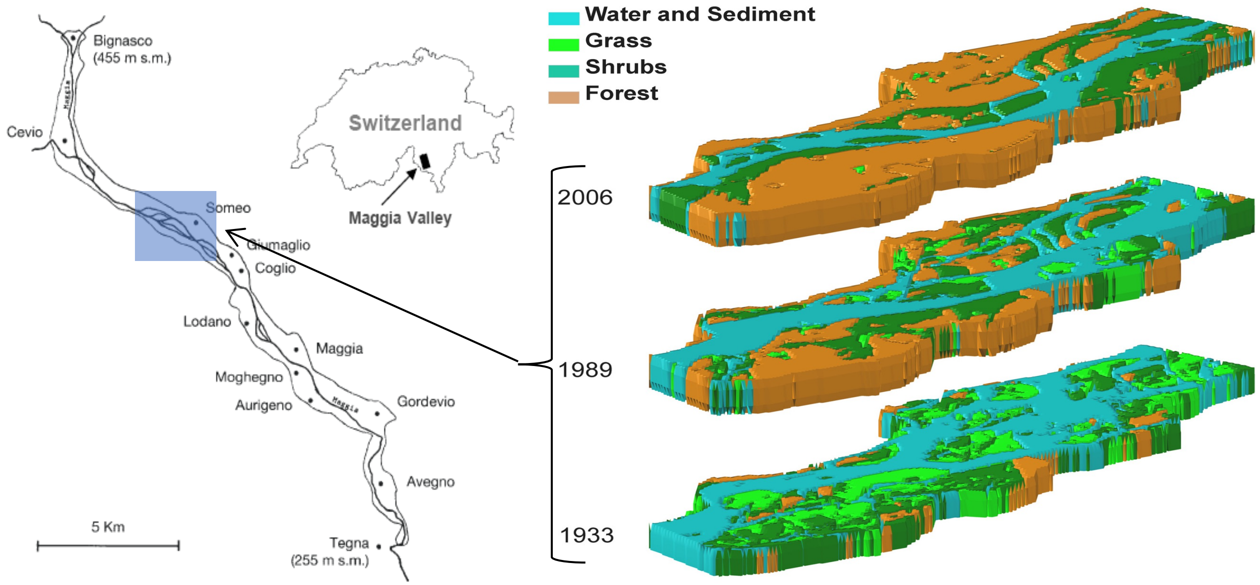
First work that puts together

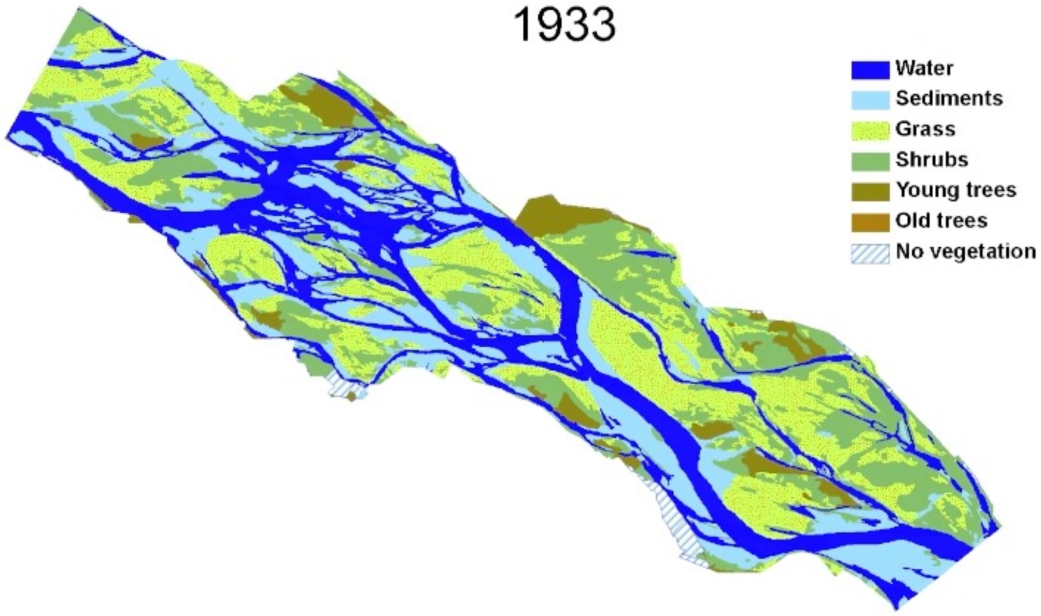
- Flow stochasticity
- Morphodynamics
- Vegetation dynamics

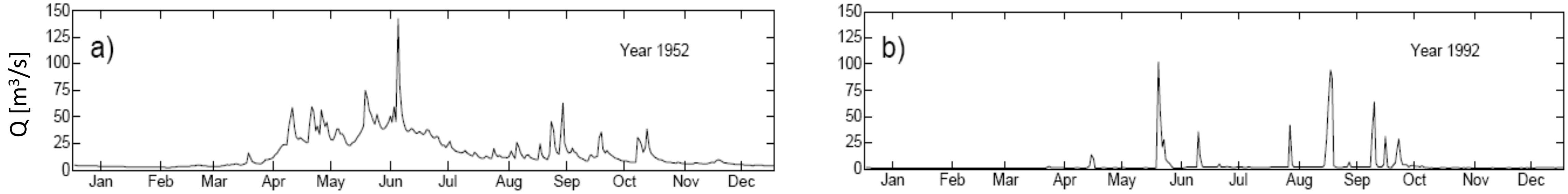
Still searching for a simplified formula that can be used for eng. applications

3. Effect of river regulation

Molnar et al., 2008; Perona et al., WRR, 2009







Master-Slave Successional Model (MSSM)

Master

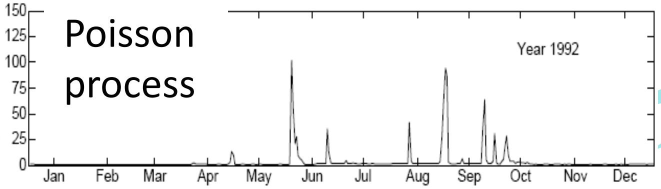
$$\frac{dA_{WS}}{dt} = \Theta(\Delta A_{SW}) \cdot \Delta A_{SW} - C_G$$

Slave

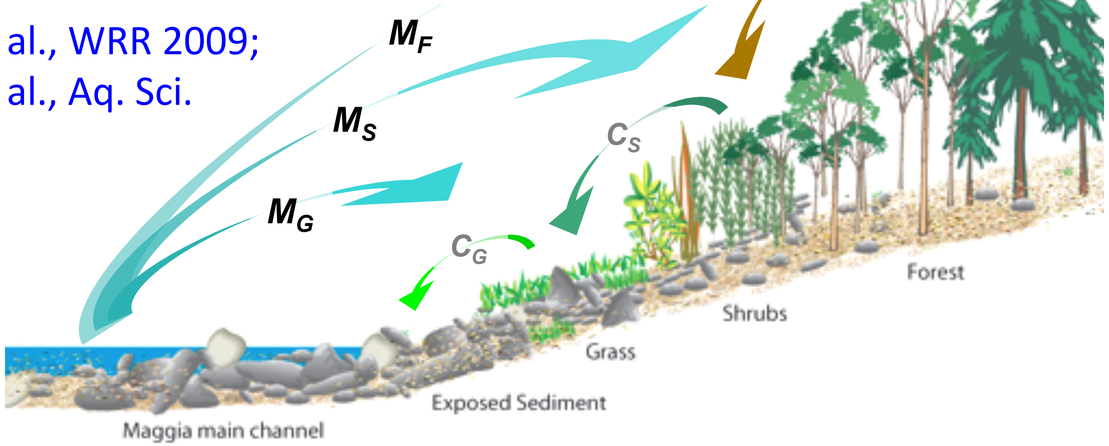
$$\frac{dA_G}{dt} = C_G - C_S - M_G$$

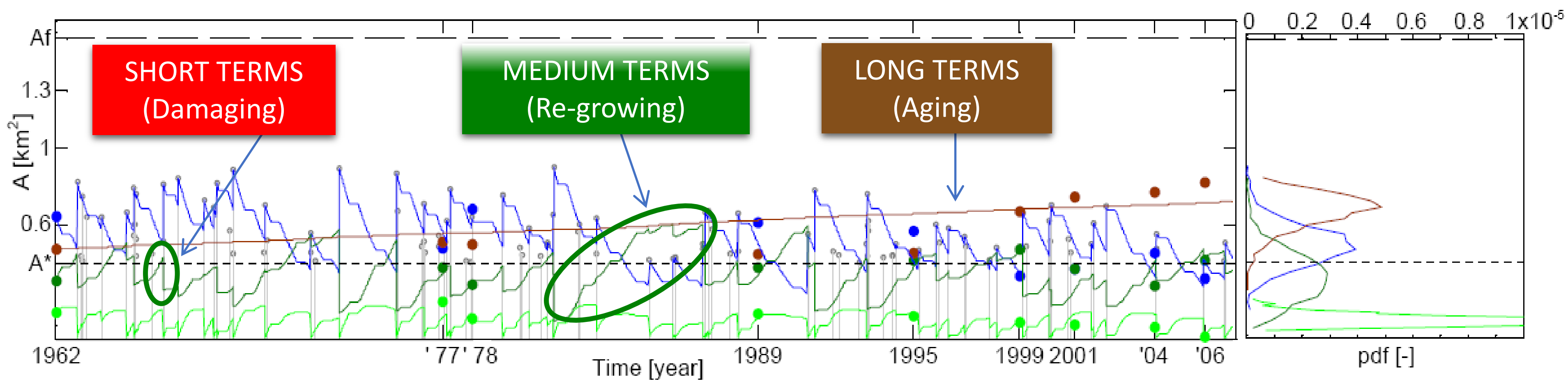
$$\frac{dA_S}{dt} = C_S - C_F - M_S$$

$$\frac{dA_F}{dt} = C_F - M_F$$

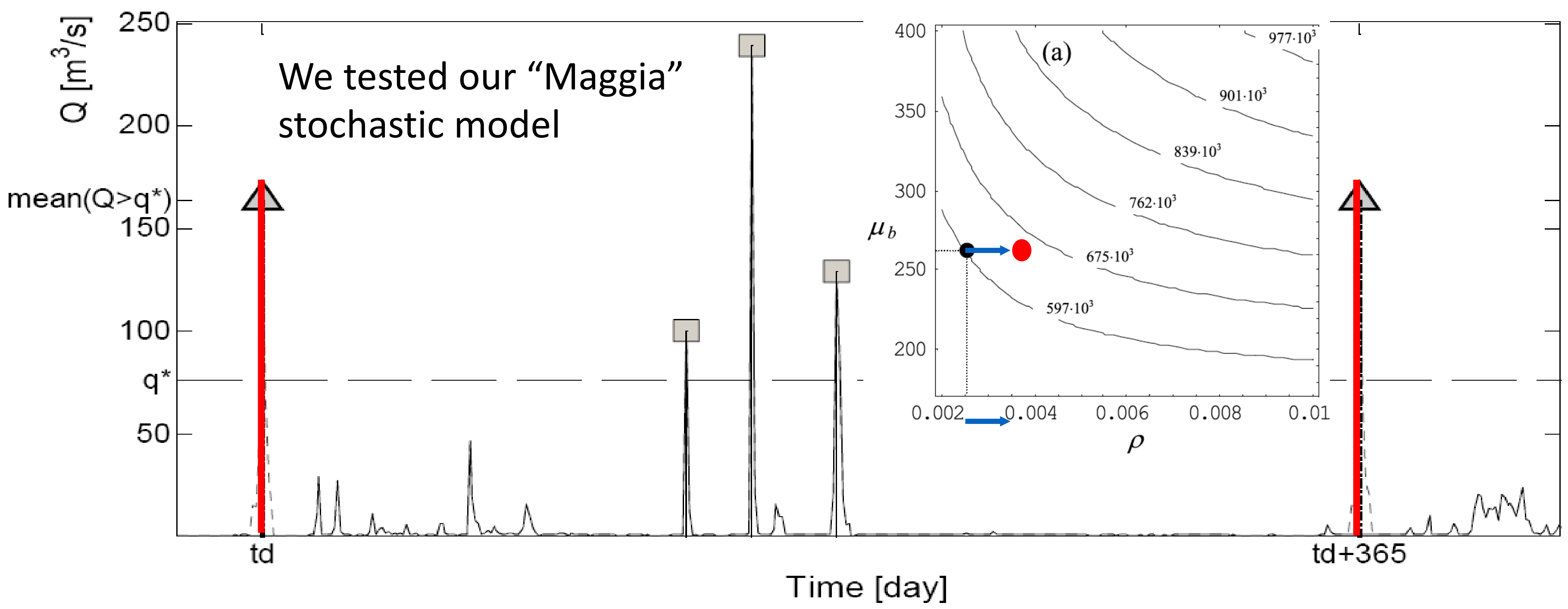


Perona et al., WRR 2009; Perona et al., Aq. Sci. 2009

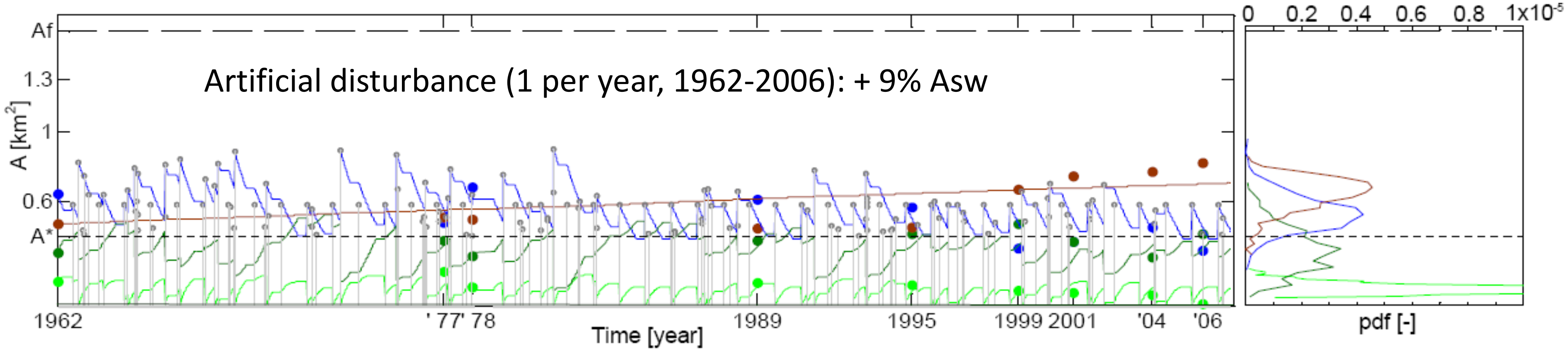




We tested our "Maggia" stochastic model

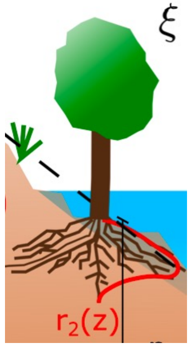


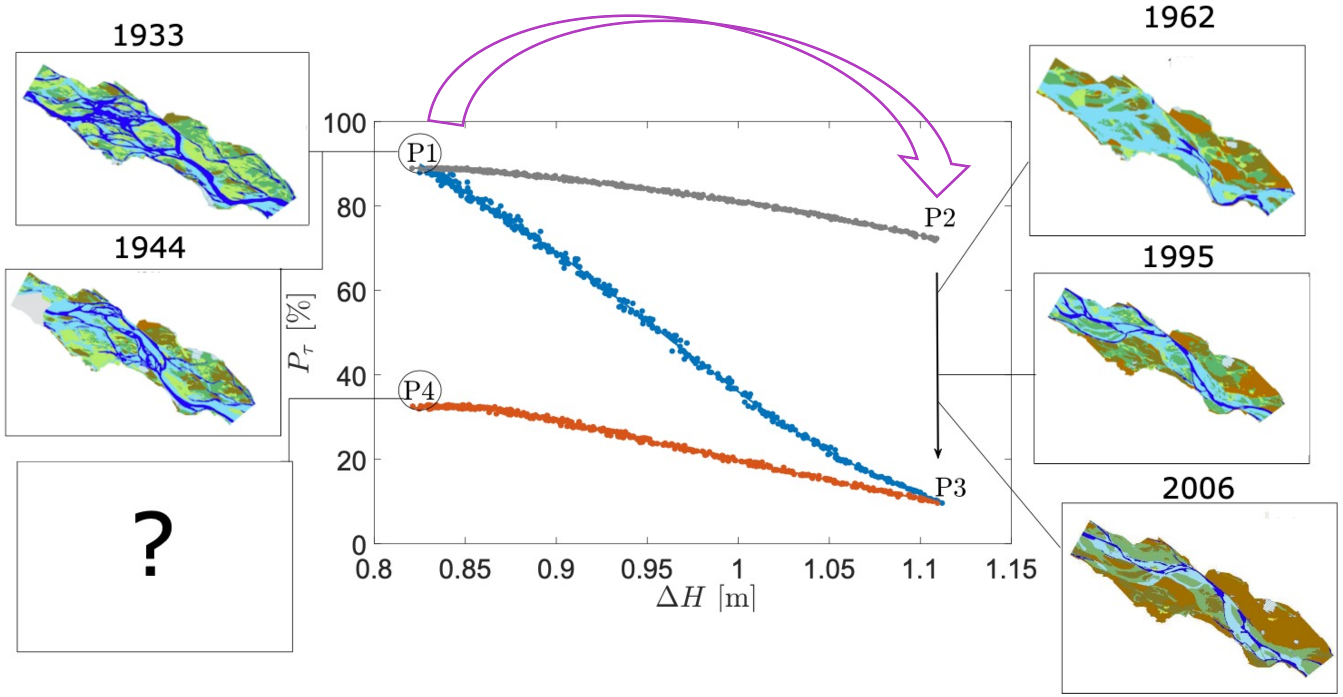
Artificial disturbance (1 per year, 1962-2006): + 9% Asw

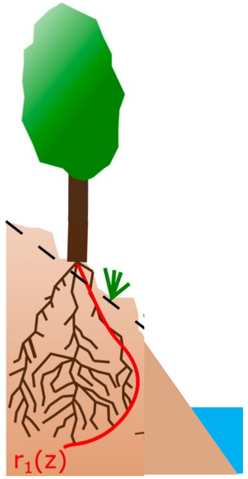


Perona et al.,Aq. Sci., 2009

4. Plant Roots Steer Resilience to Perturbation of River Floodplains







Bau, PhD thesis, 2020
Bau et al., GRL, 2021