River ecomorphodynamics and bioengineering

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

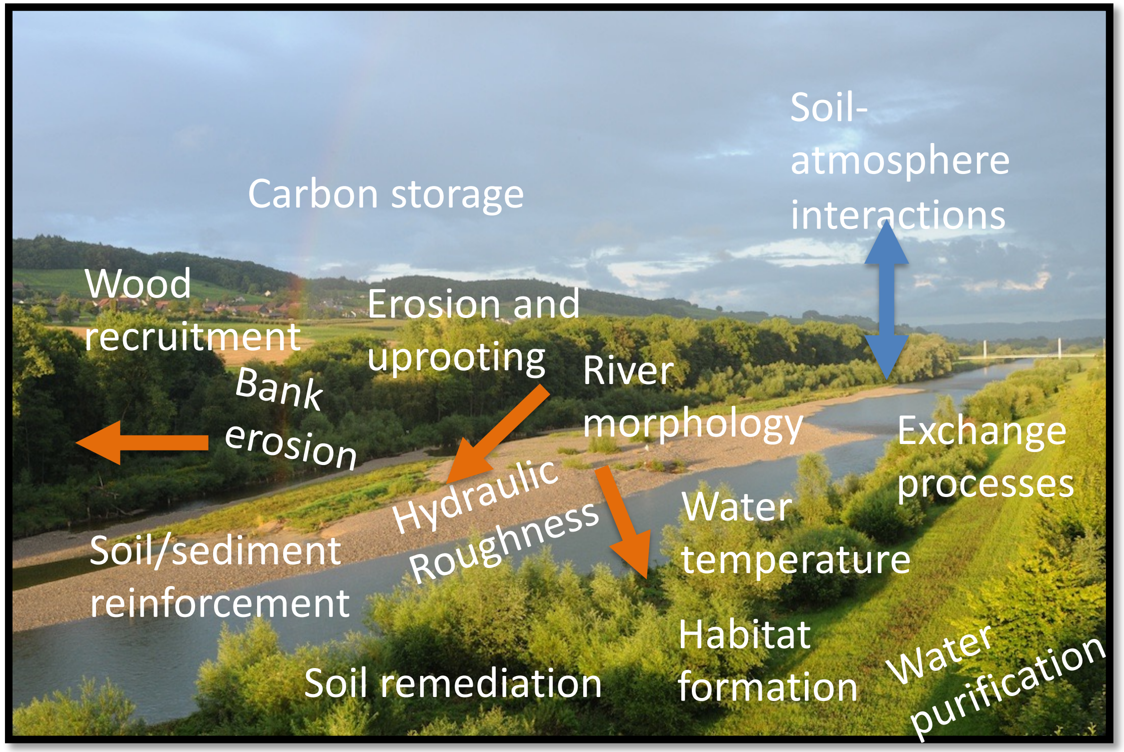
4ETCS, Master option

Prof. Paolo Perona
Platform of Hydraulic Constructions

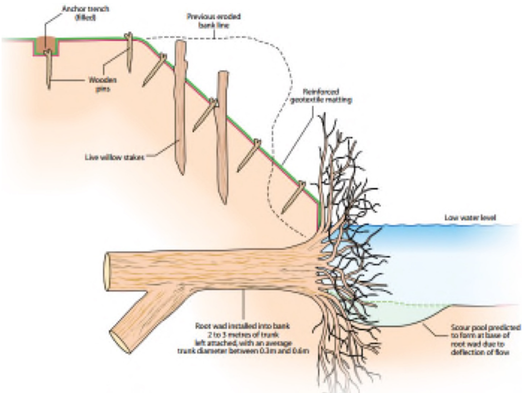
Lecture 12-1: Riparian vegetation, canopy and roots

Interest in riparian vegetation

- Riparian vegetation is an active component with multiple functions for the riverine ecosystems
- Growing next to water courses, it determines both passive and active feedbacks with river dynamics
- Contributes to form river styles and patterns
- Pioneering species contribute to form new habitats (ecological niches)
- Very relevant for sustainable bioengineering approaches but also determines hydraulic risk (bank erosion, LW clogging, etc)




Luther Water, Scotland, UK



Which riparian plants

- Willows and poplars (Family Salicaceae), several species, fast growth, waterlogging tolerant, etc
- Ubiquitous along river Northern hemisphere, invasive elsewhere
- Pioneer species: keystone succession element
- Ecosystem engineers
- Sprout roots from cutting branches
- Largely used in experimental ecohydraulics

Populus nigra (Black pupulous)

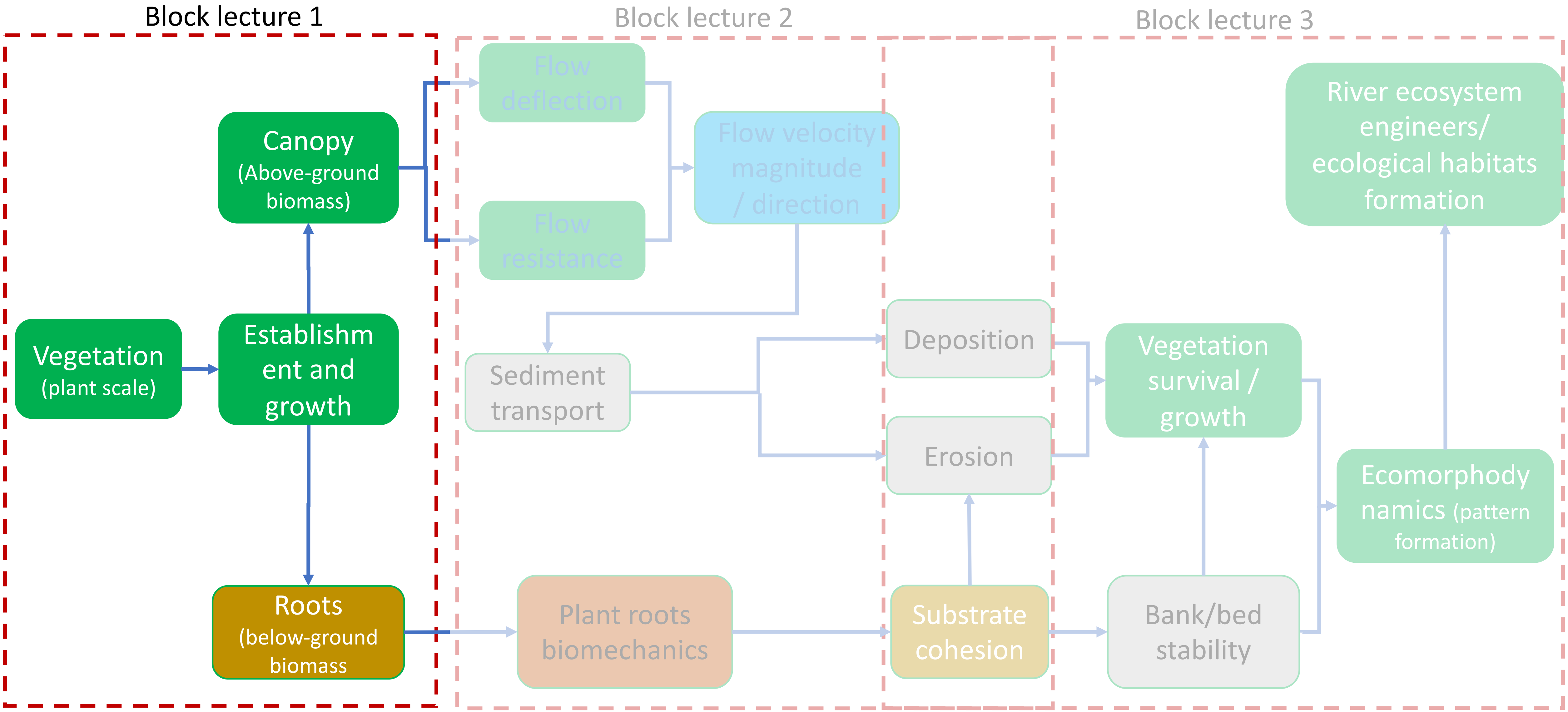
Salix Alba (White willow)

Naturally established

Resprout from LW deposits

Bioengineering techniques (cuttings)

Salicacee and fluvial processes



Above-ground biomass

Establishment and growth at the field scale

Seed recruitment

➢ Salicaceae are heliophilous
- Require bare ground

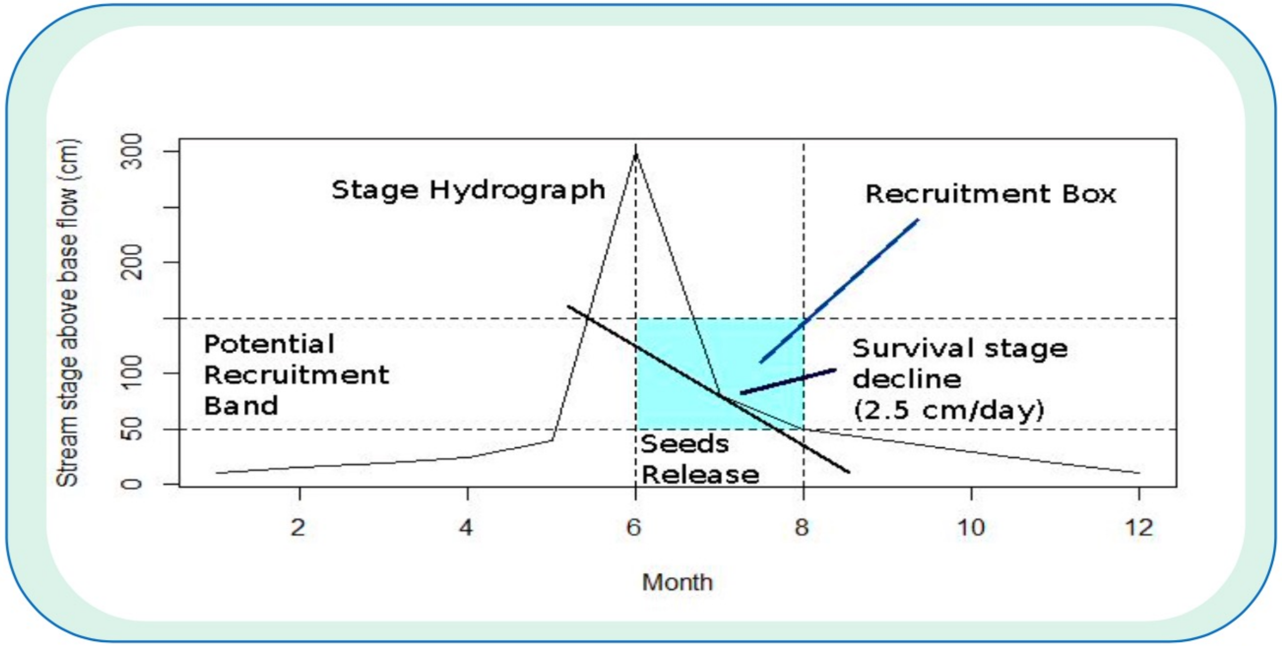
➢ Short-lived seeds ~ 20 days
- Require moist substrate

➢ Seeds dispersal sync with annual peak
- Floods create bare nursery sites
- Receding wave provides moisture

➢ Roots track declining stage
- Max decline 2 - 3 cm/day
- Max root growth 1.5 - 1.7 cm/day

➢ Recruitment box model (Mahoney and Rood 1998)

➢ Recruitment "bands"



Mahoney, J.M., Rood, S.B., 1998. Streamflow Requirements for Cottonwood Seedling Recruitment An Integrative Model. Wetlands 18, 634–645

Growth of willow cuttings

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

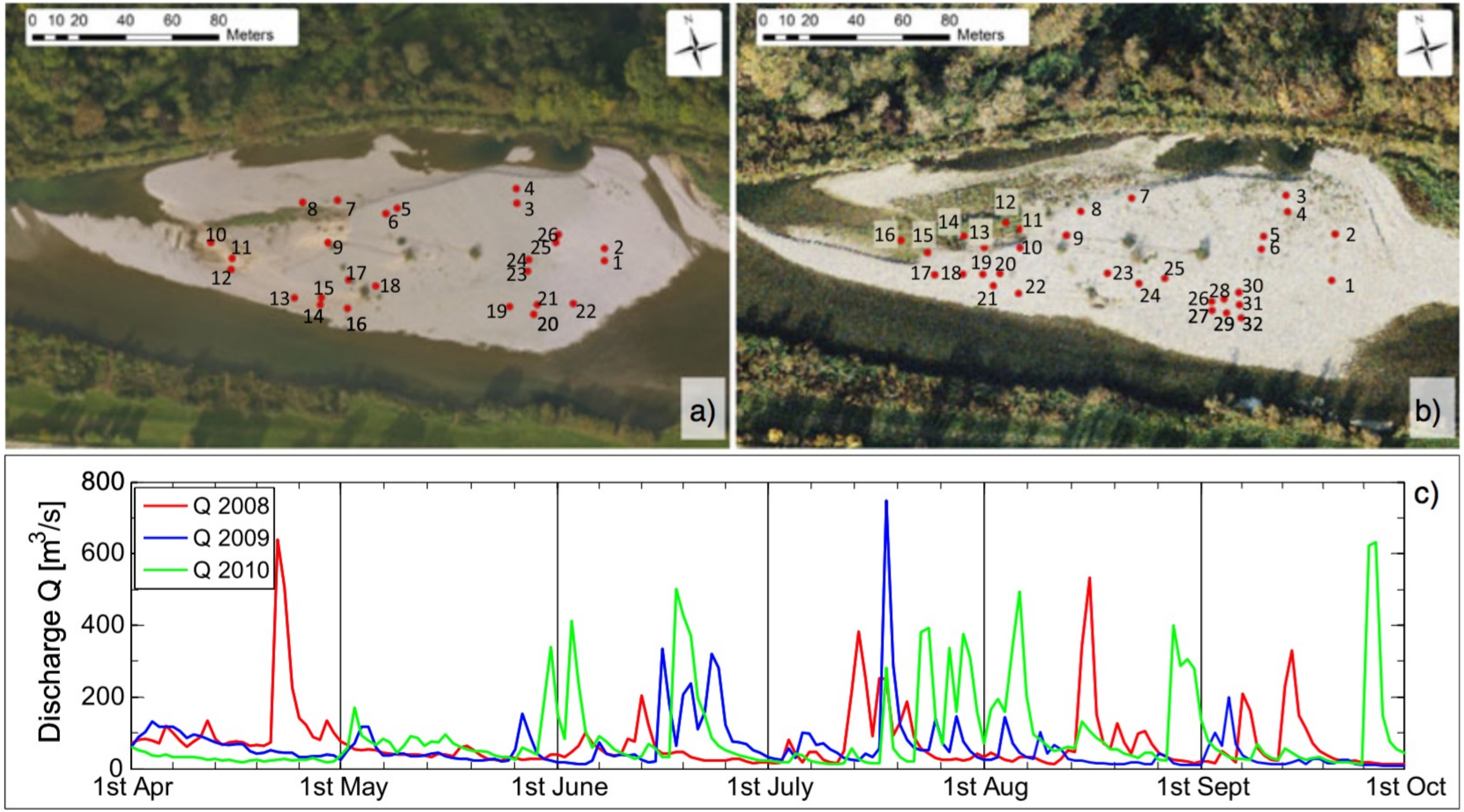
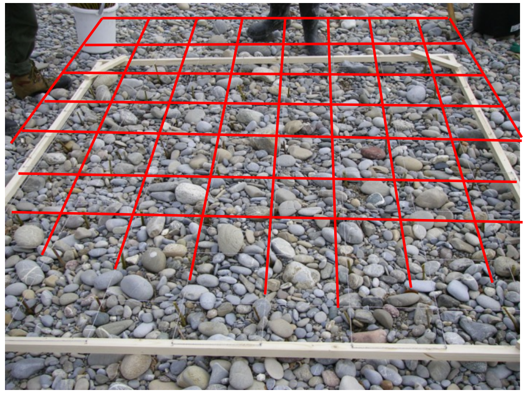


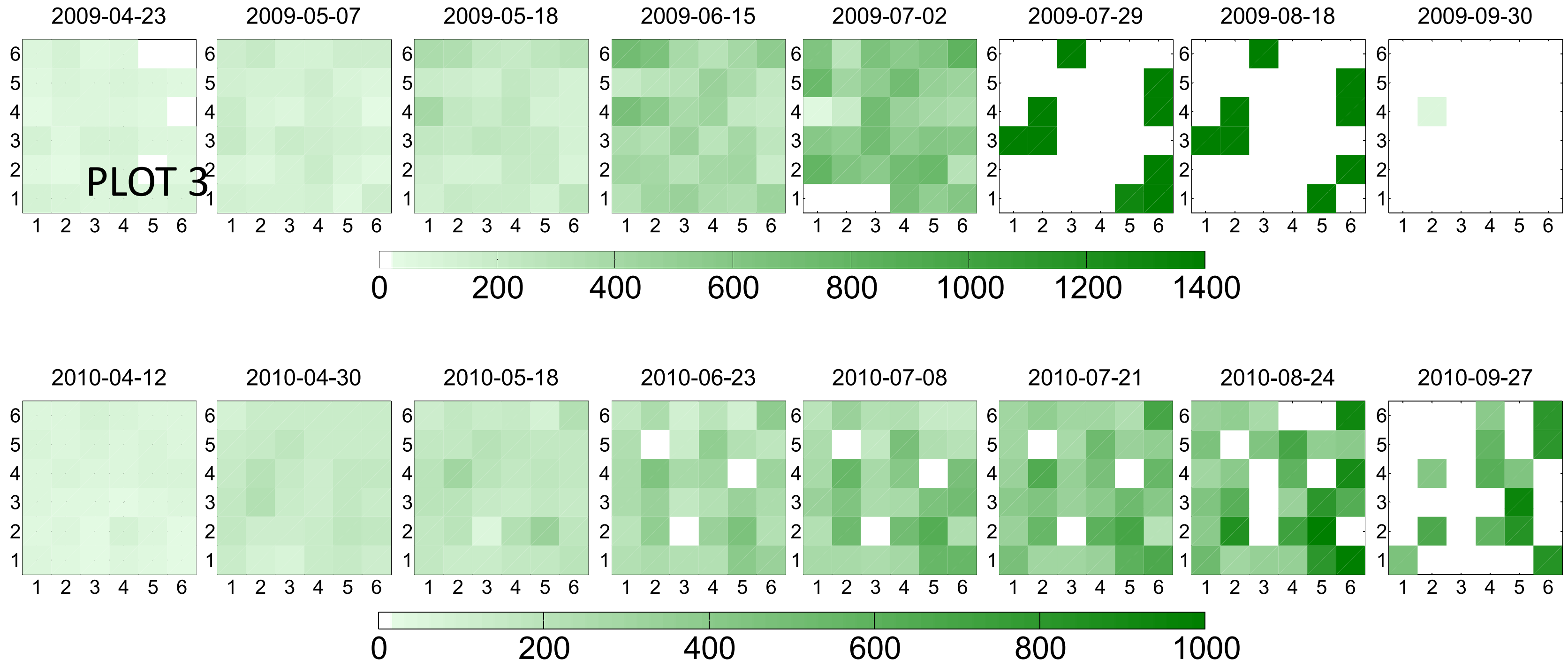
Figure 3. Map of the investigated island showing the location of the vegetation plots in 2009 (a) and 2010 (b). Plot locations have been identified mainly according to hydraulic parameters (flow, shear stress and velocity) and to topography (elevation). Frame (c) shows the hydrographs of the corresponding years

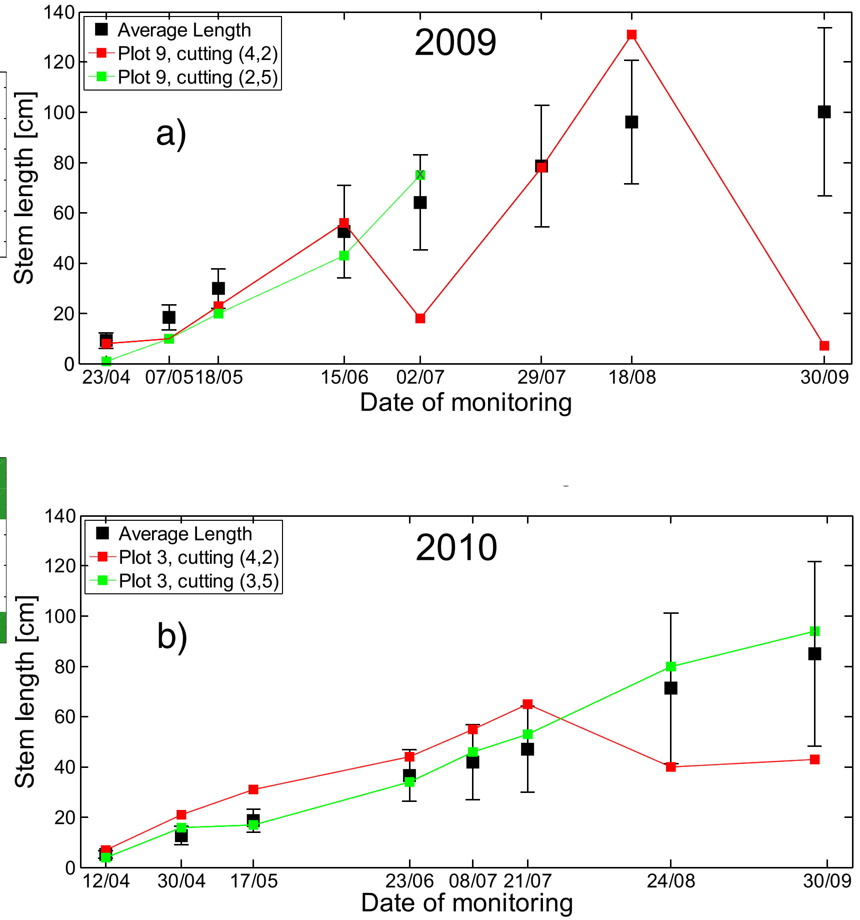
- 2 Field campaigns (09;10)
- ~ 1200 Salix cuttings in 26 Plots (2m x 2m) with different densities (9 and 20 plants/m^2)



PLOT 9

From: Pasquale, Perona et al., Hydr. Proc. 2014





Two plots growth dynamics:

Color intensity represents the length of the longest branch in the cutting

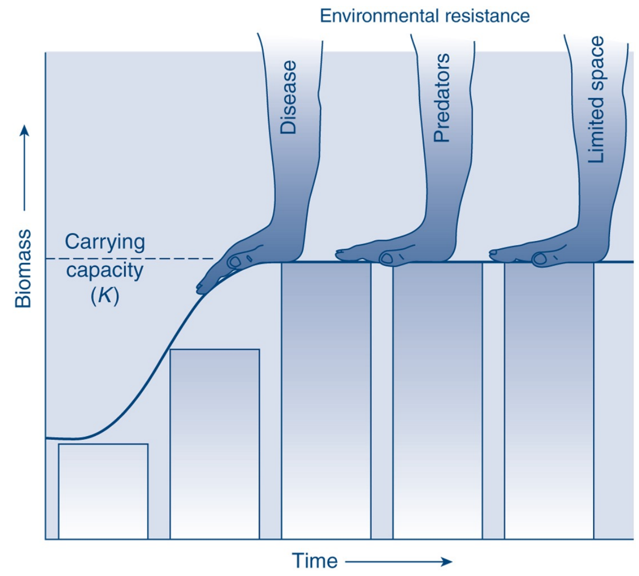
Logistic growth models

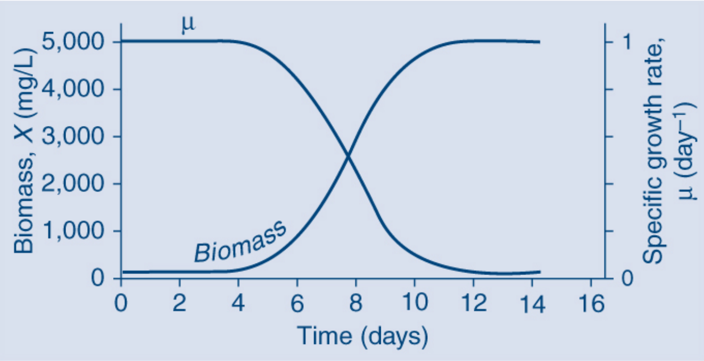
The effect of carrying capacity:
Logistic growth model

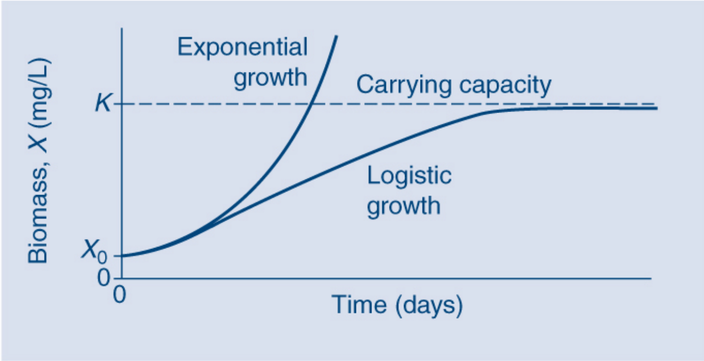
$$\frac{dX}{dt} = (\mu_{\max} - k_d)\left(1 - \frac{X}{K}\right)X$$

$$X(t) = \frac{K}{1 + \left[\left(\frac{K - X_0}{X_0}\right) e^{-(\mu_{\max} - k_d)t}\right]}$$

Useful to describe environmental resistance to grow, but no predators







Other similar models

Vegetation growth (Logistic Verhulst equation) and decay (Camporeale, 2006; Perona et al., 2014)

$$\frac{dv}{dt} = v^m(\beta - v)^p \qquad \text{Growth}$$

$$\frac{dv}{dt^*} = -\alpha_1 v^n \qquad \text{Decay}$$

…or the JABOWA equation (Botkin et al., 1972)

$$\frac{d\vartheta}{dt^*} = \frac{G(\vartheta D_m^*)^{q-1}\left[(\vartheta^3 - 2\vartheta^2 + 1)H_m^* - (\vartheta - 1)^2 \vartheta H_0^*\right]}{2\left[H_0^* + \vartheta(2\vartheta - 3)(H_0^* - H_m^*)\right]H_m^*}$$

Discrete logistic map

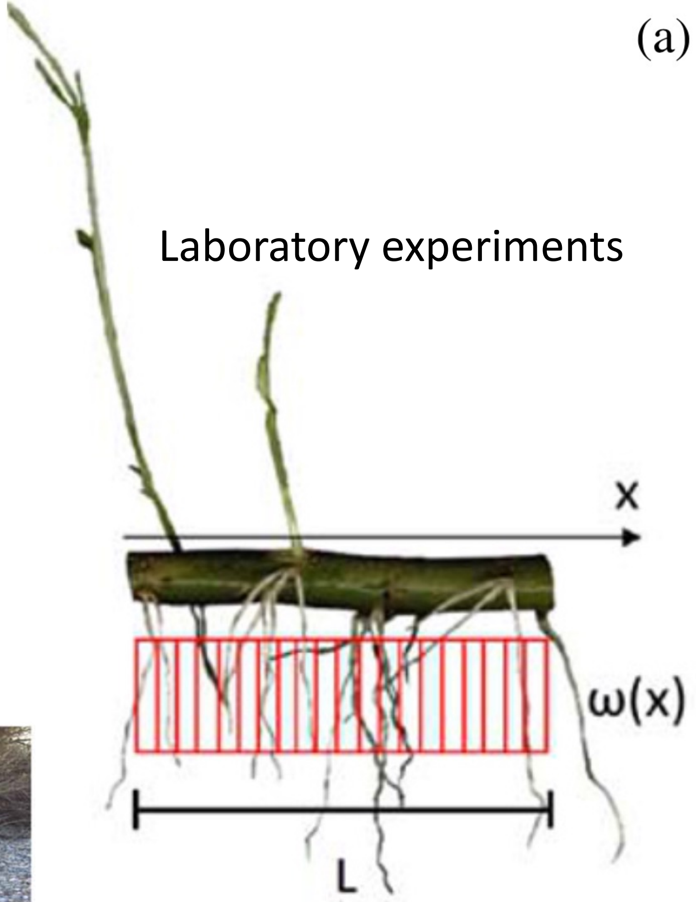
$X_{n+1} = a\,X_n(1 - X_n)$

Very interesting behaviour for changing a!

Large wood logs

- •LW created & deposited by floods
- •➢ Favourable locations:
  - o Low enough to provide moisture
  - o High enough to prevent re-mobilization
  - by subsequent floods
- •➢ Key regeneration process in highly dynamic rivers

Laboratory experiments



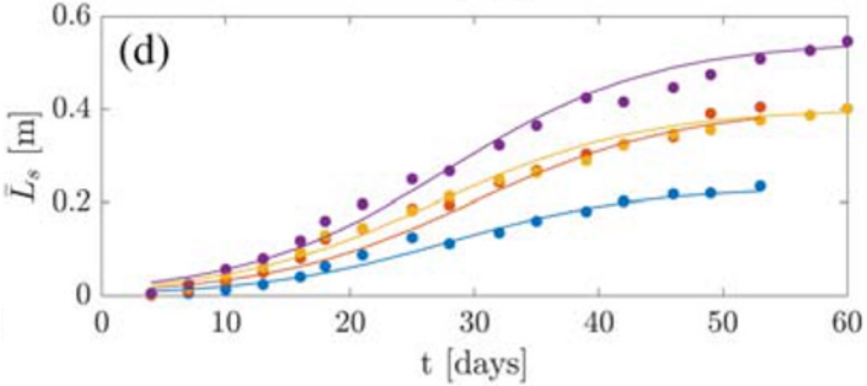
Logistic equation (Verhulst, 1840) for biomass amount X(t)

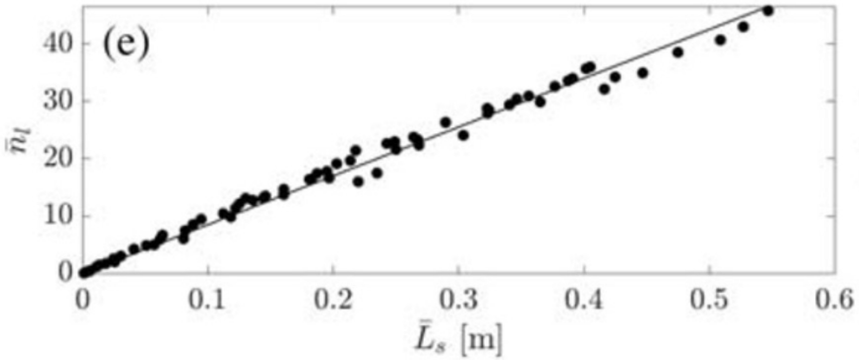
$$\frac{dX}{dt} = (\mu_{\max} - k_d)\left(1 - \frac{X}{K}\right)X$$

$$X(t) = \frac{K}{1 + \left[\left(\frac{K - X_0}{X_0}\right) e^{-(\mu_{\max} - k_d)t}\right]}$$

Bau and Perona, JGR 2020

$$\bar{L}_s(t) = \frac{\bar{L}_{s,\,max}}{1 + e^{-b(t - t_0)}}$$





Number of leaves correlates linearly with total stem length

Below-ground biomass

Riparian landscapes shaped by plant roots evolution (e.g., Gibling and Davies, Nature Geosci. 2013)

→ Definitive early roots in the paleozoic

→ Increased biogeomorphic complexity

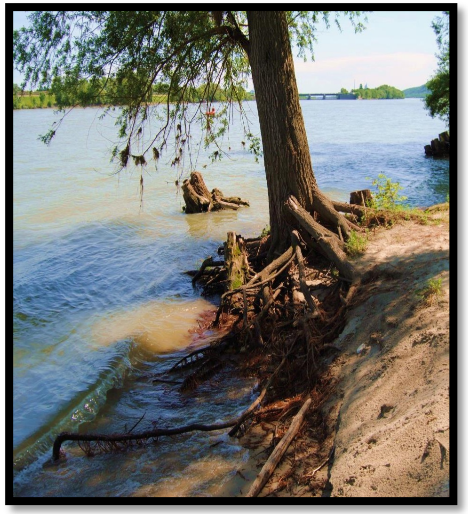
→ Favored aquatic → terrestrial species

Plant root functions in riparian environments (e.g., Waisel et al.)

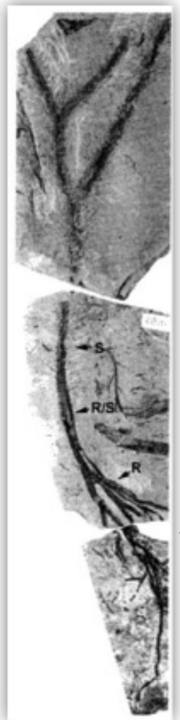
→ Increase soil cohesion of the riverbank

→ Influence biogeochemical processes in the soil

→ Sustain below-ground biodiversity



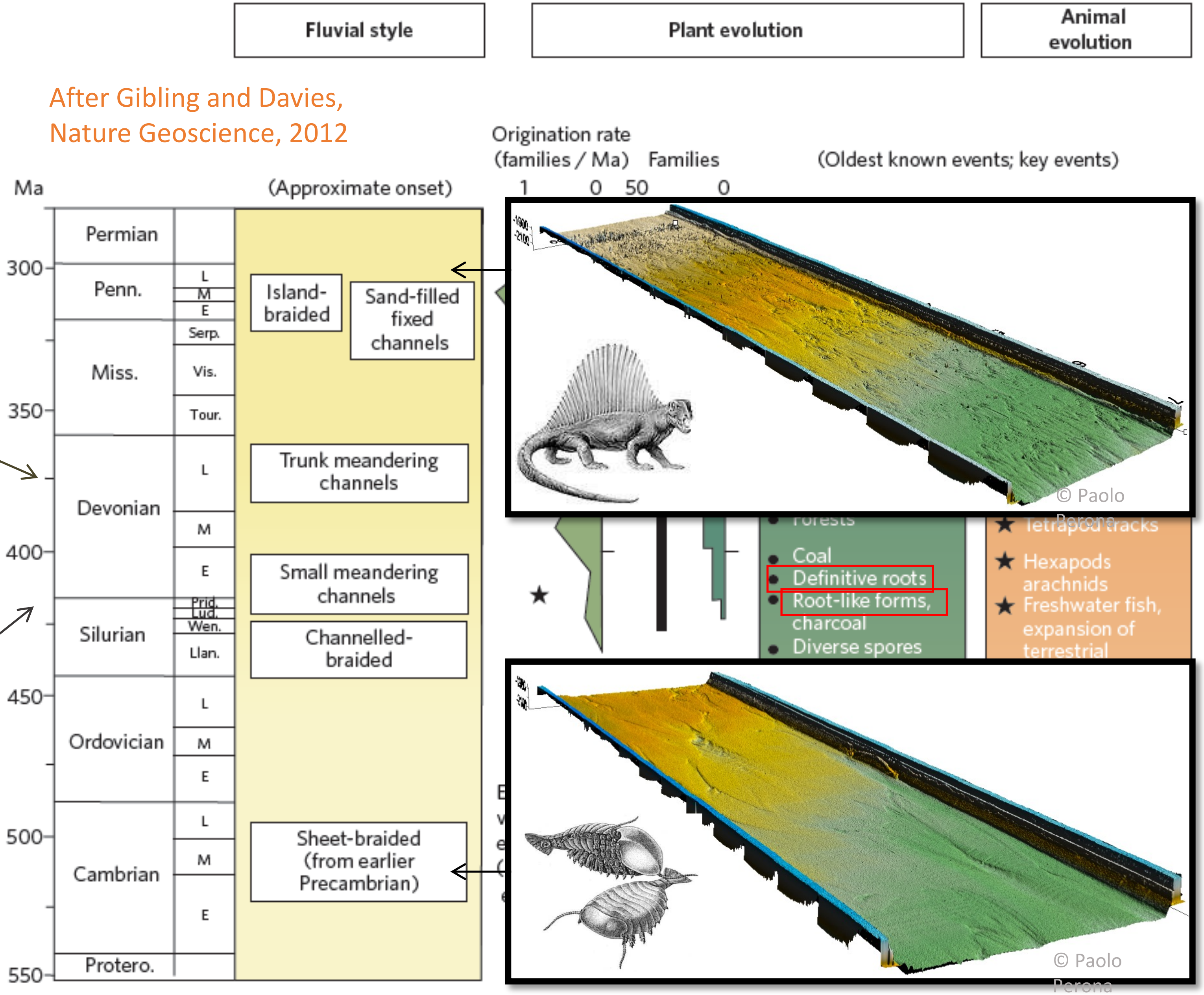
Paleozoic landscapes shaped by plant roots evolution



Chamaendendron multisporangiatum

From Waisel et al, 2002

After Gibling and Davies, Nature Geoscience, 2012



Ancient root systems: (Bottom) The oldest (396 Mio ys) rooting structure preserved in growth position; (Top) A 377 Mio-ys-old root of *Chamaendendron multisporangiatum* showing multiple bifurcations on both the root (R) and the Stem (S). Source: Waisel et al., Plant Roots: the hidden half

Plant roots growth: tropism actions

"Tropism" is the response of biological systems to environmental stimuli

- Gravitropism (Geotropism): root response to gravity (Knight, 1811)
- Hydrotropism: response to soil moisture gradients(Sachs 1872)
- Phototropism: response to light sources (Darwin, 1881*)
- Thigmotropism: response to mechanical impedence (Darwin, 1881)
- Oxytropism (aerotropism): response to oxygen concentration (Pfeffer, 1906)
- Chemotropism: response to nutrients (chemicals) concentration
- Plagiotropism: response to temperature gradients (Kaspar and bland 1992)

Pea root growth

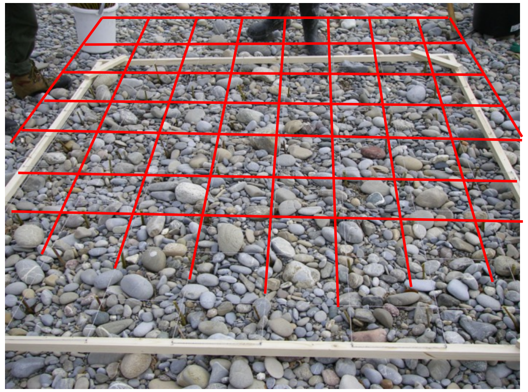
Darwin and Darwin, The power of movement in plants, 1881

Root growth

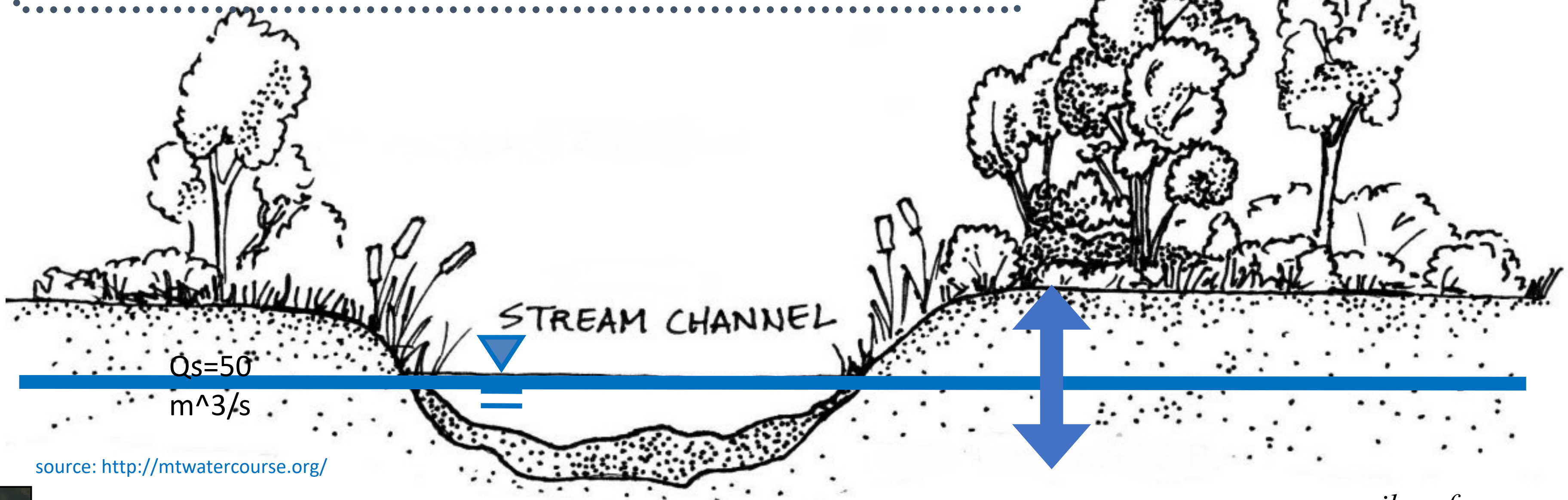
Salix Alba

Salix Nigricans

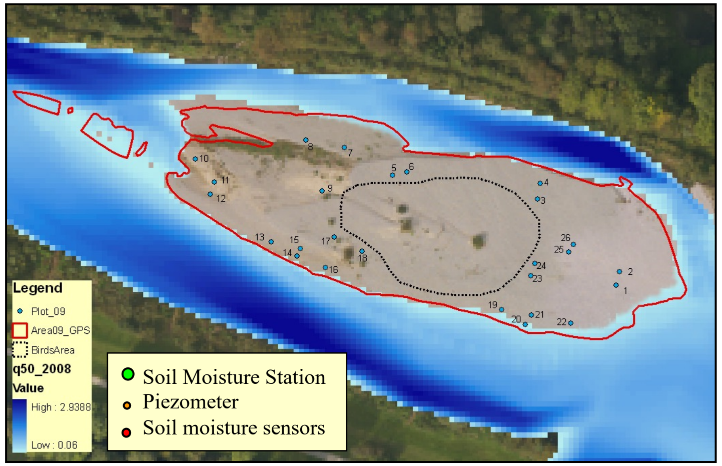
Salix Purpurea



Differently from rainfed upland, river level fluctuations may shape the vertical root profile of vegetation cuttings*!



source: http://mtwatercourse.org/



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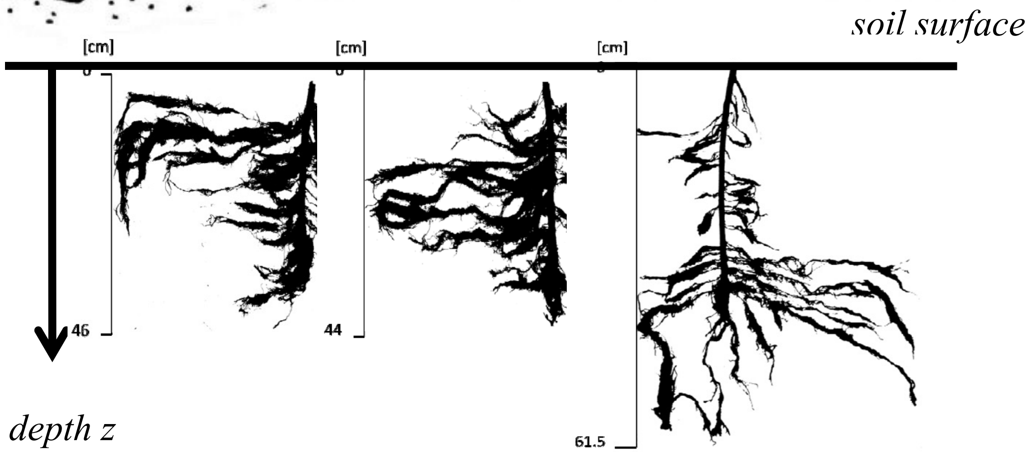
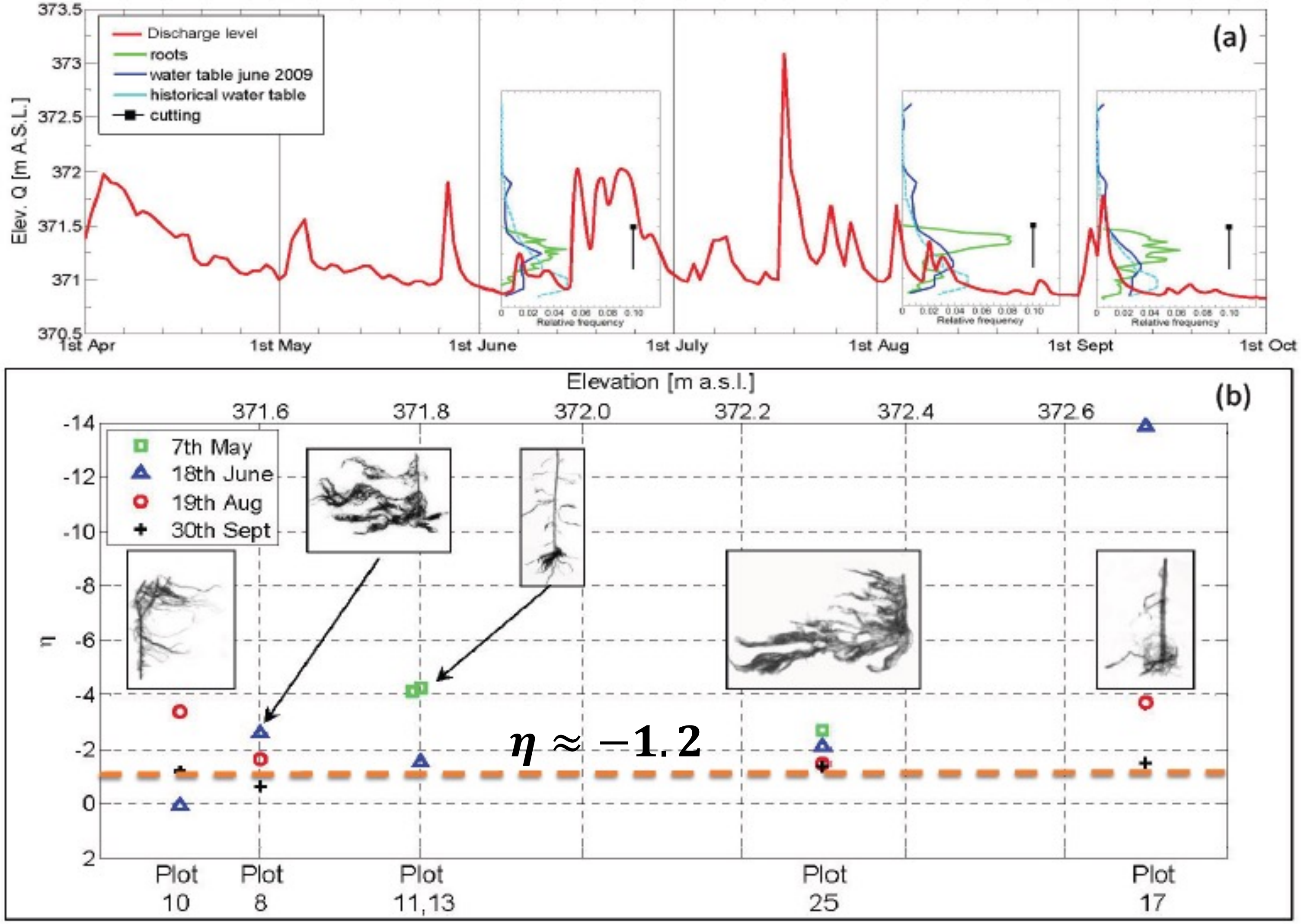


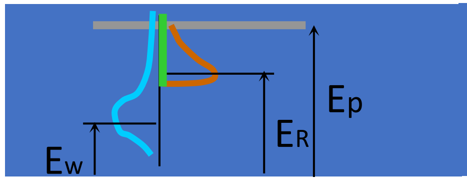
Pasquale, Perona et al. Ecol. Eng., 2012

Dimensionless root mode depth-to-surface

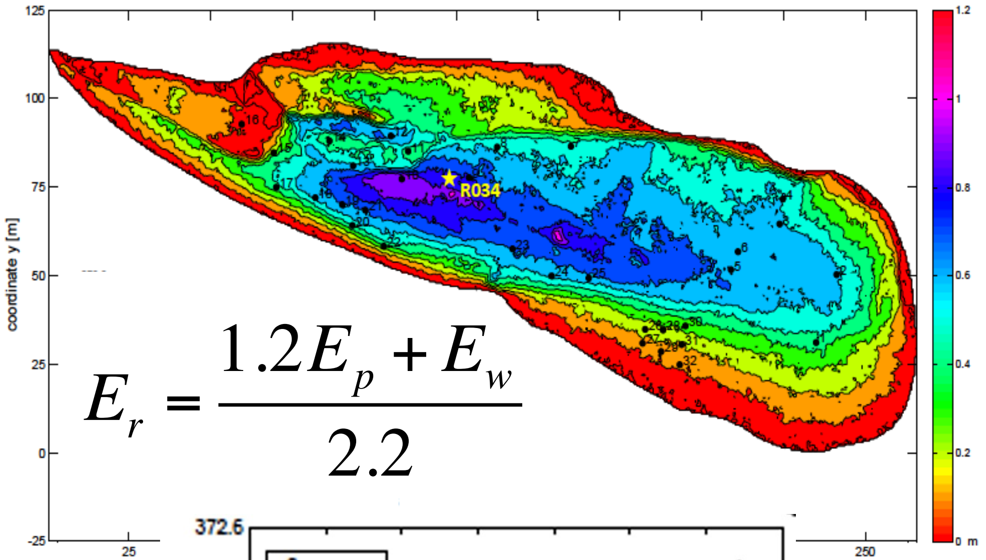
After Pasquale, Perona et al., Ecol. Eng., 2012



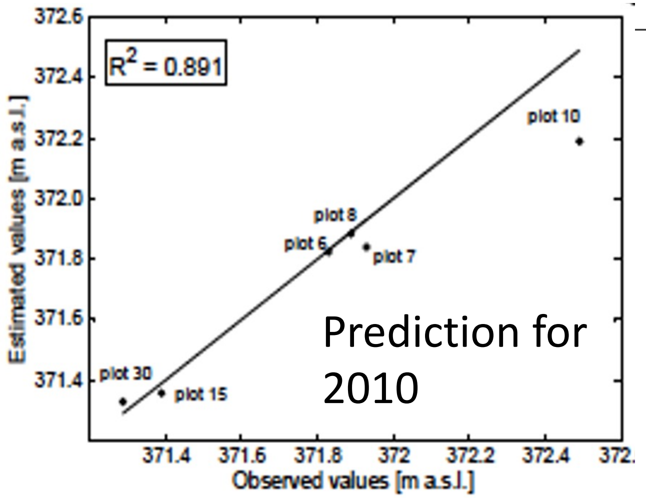
$\eta \approx -1.2$



$$\eta = \frac{E_W - E_R}{E_P - E_R}$$

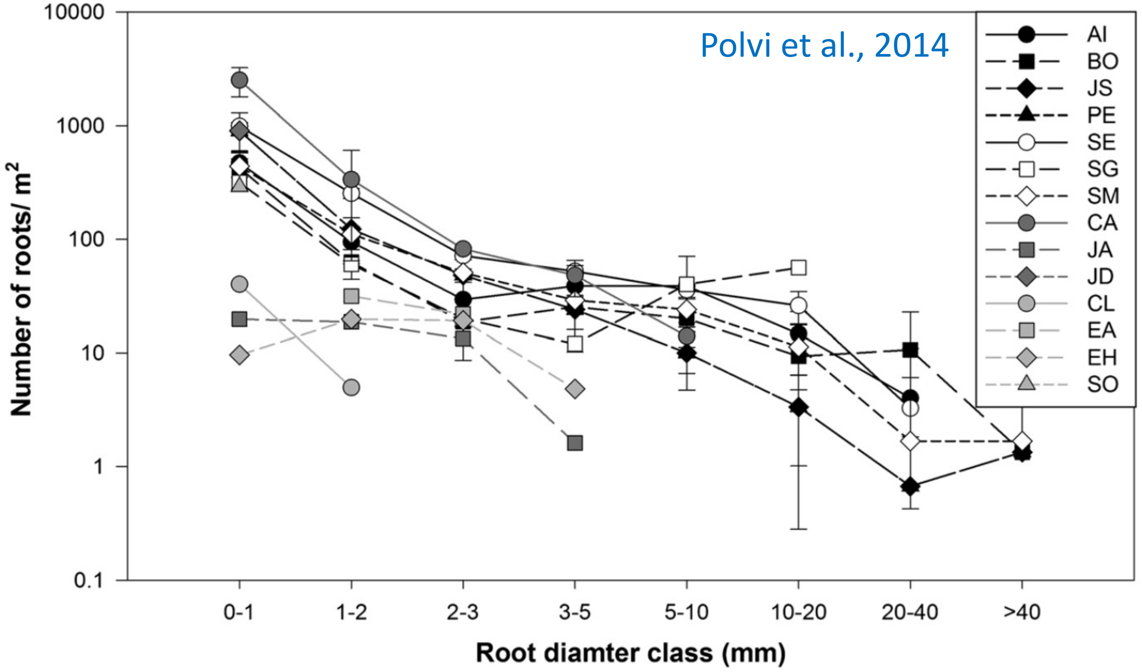


$$E_r = \frac{1.2E_p + E_w}{2.2}$$



Prediction for 2010

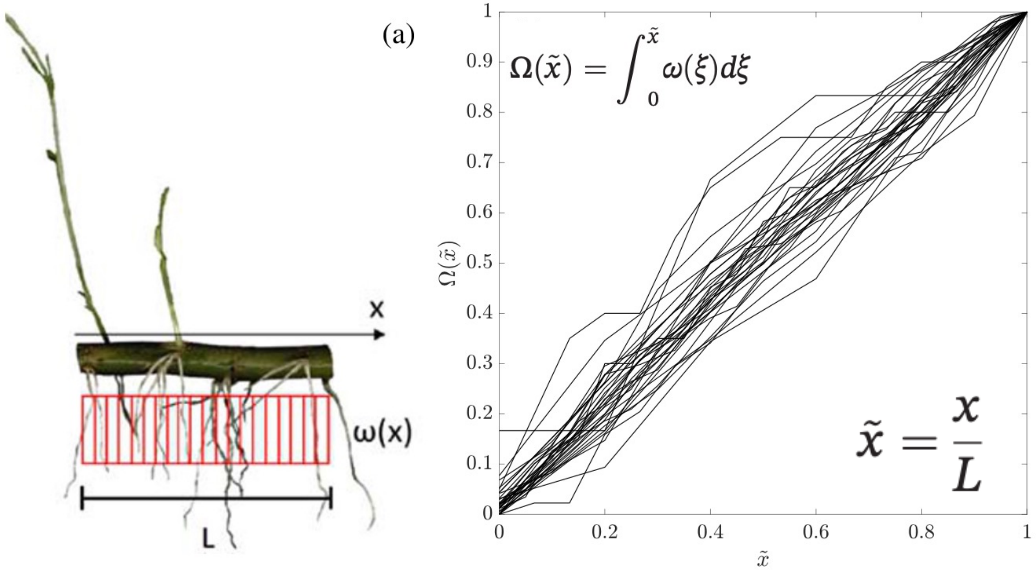
Some root characteristics of riparian vegetation



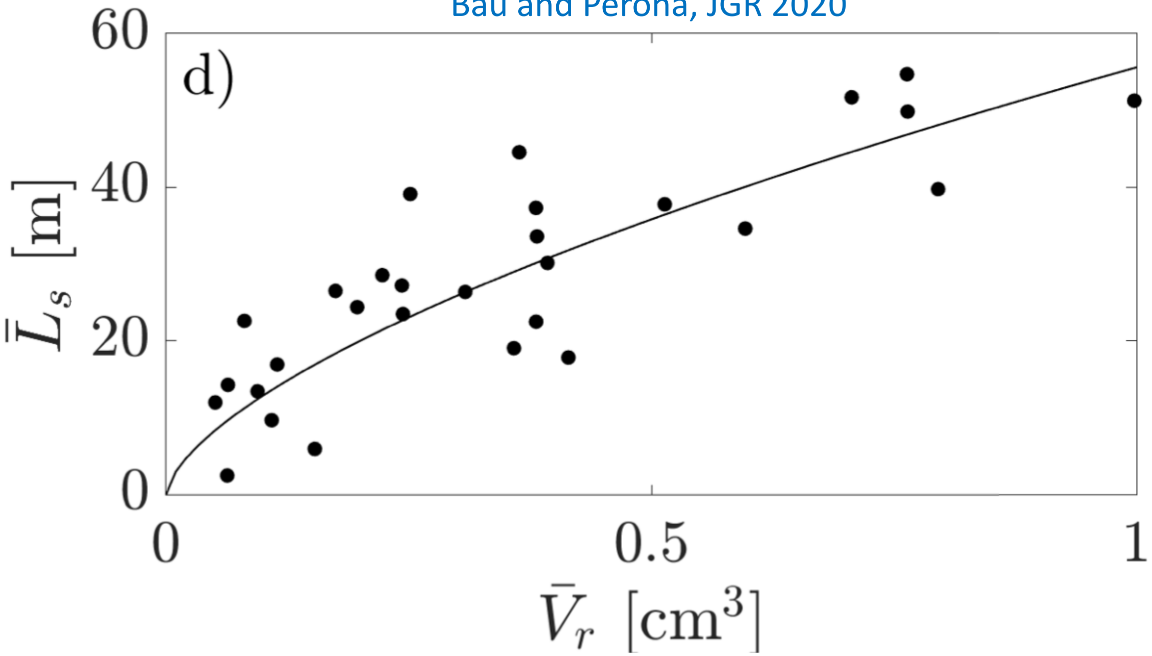
Vegetation group	Root depth (m)				Lateral root extent (m)			
	Min.	Max.	Mean	Range	Min.	Max.	Mean	Range
Tree	0.4	1.0	0.59	0.6	0.5	1.0	0.75	0.5
Shrub	0.2	0.9	0.46	0.8	1.0	1.0	1.00	0.0
Graminoid	0.3	0.6	0.43	0.3	0.1	0.5	0.23	0.4
Forb	0.3	0.5	0.38	0.2	0.1	0.4	0.25	0.3
p-Value			0.181				*0.002*	

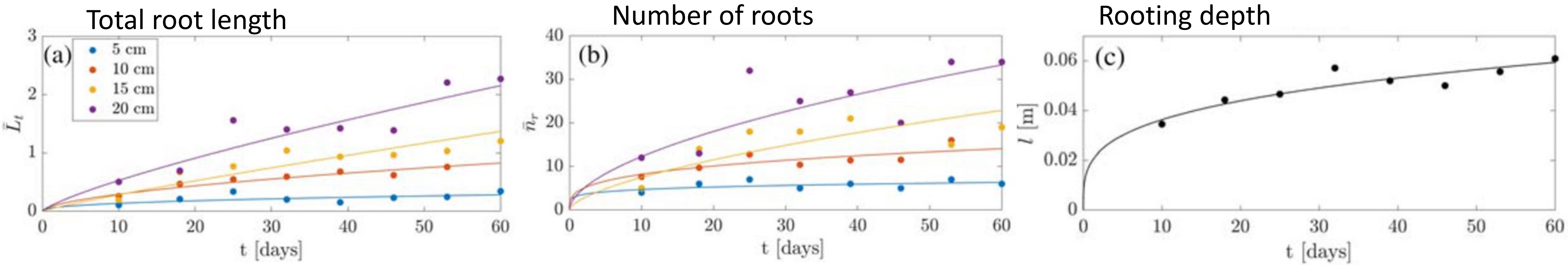
Latin name	Abbreviation	Common name	Vegetation group
Alnus incana	AI	gray alder	Tree
Betula occidentalis	BO	western birch	Tree
Caltha leptosepala	CL	marsh marigold	Forb
Carex aquatilis	CA	water sedge	Graminoid
Equisetum arvense	EA	field horsetail	Forb
Equisetum hyemale	EH	scouringrush horsetail	Forb
Juncus arcticus	JA	arctic rush	Graminoid
Juncus drummondii	JD	Drummond's rush	Graminoid
Juniperus scopulorum	JS	western juniper	Tree
Picea engelmannii	PE	Engelmann spruce	Tree
Salix exigua	SE	sandbar willow	Shrub
Salix geyeriana	SG	Geyer willow	Shrub
Salix monticola	SM	mountain willow	Shrub
Saxifraga odontoloma	SO	brook saxifrage	Forb

Re-sprouting of Large Wood Deposits



Bau and Perona, JGR 2020

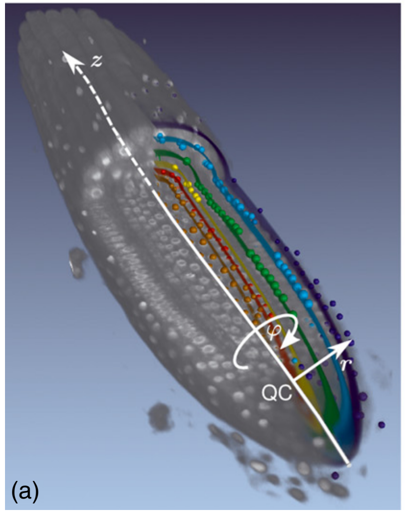




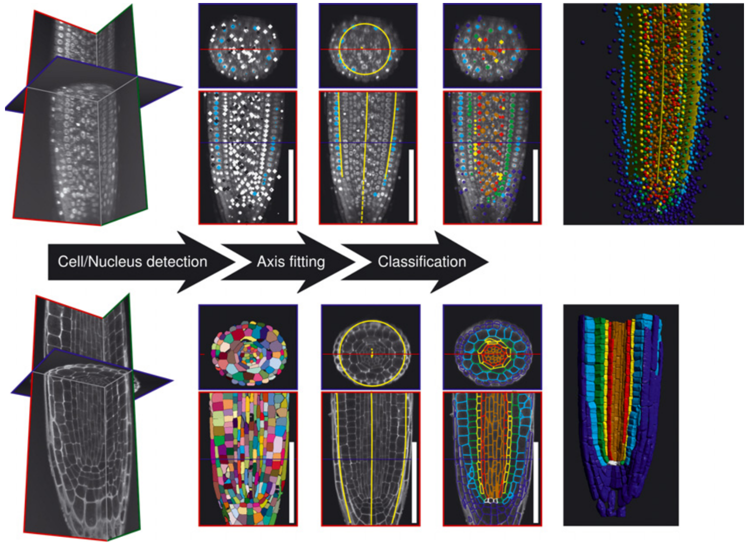
Root growth models

Root analysis and architecture models

The iRoCS Toolbox – 3D analysis of the plant root apical meristem at cellular resolution (Schmidt et al., Plant Journal, 2014)

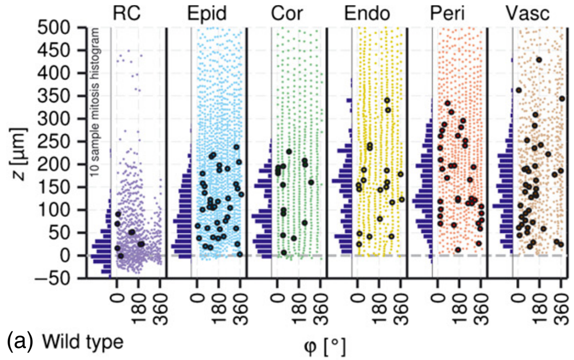


Root description



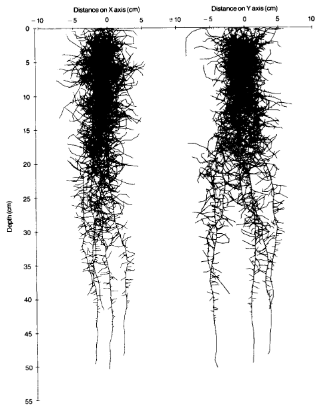
Root "pipelines"

Cumulated median statistics concerning hormon fluxes within cell tissues

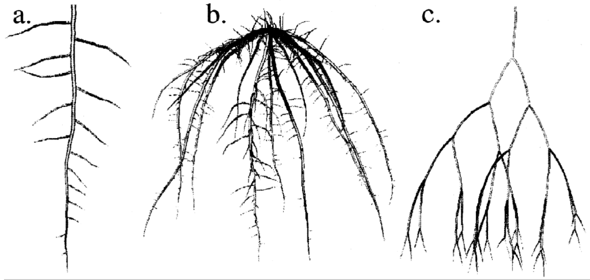


- 3D-Geometric models
- Based on a number of predefined (probabilistic) geometric rules, e.g.:
  - ➢ Number of branches
  - ➢ Branching length
  - ➢ Branching angles

ROOTMAP
(The Australian School, Diggle, Plant & Soil, 1988)



SIMROOT
(The American School, Lynch et al., Plant & Soil, 1997)

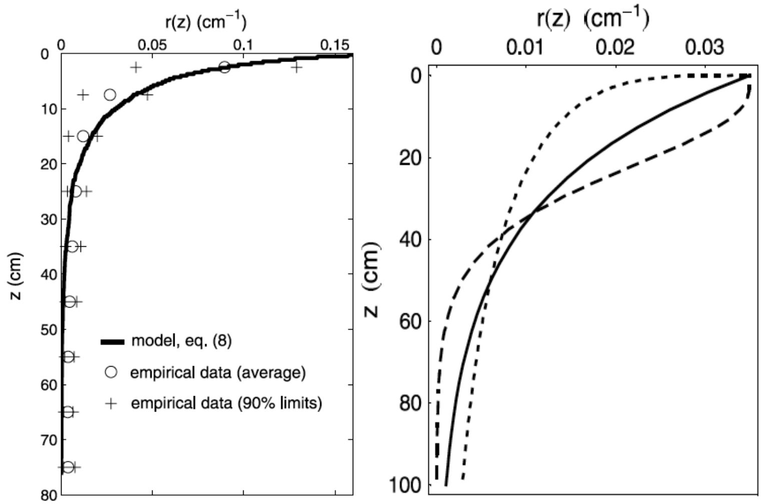


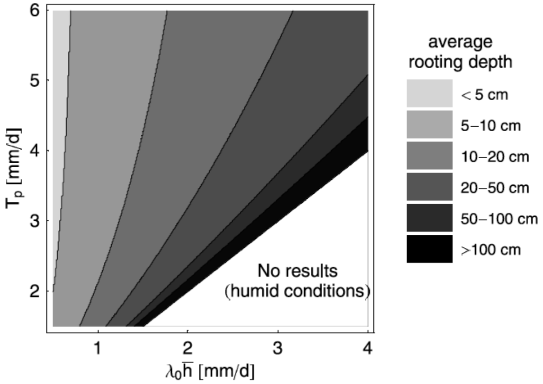
Includes some kinematics functions and generates "solid" 3-D roots

Root density models (1D)

The Italian School, Ecohydrology
(Laio, WRR, 2006,
Laio et al., GRL, 2006; Tron et al., 2014)

$$r(z) = \frac{\lambda_0 n (s_{fc} - \bar{s})}{T_p \bar{\rho}(s)} \{1 - P_H [nz(s_{fc} - \bar{s}_m(z))]\}.$$

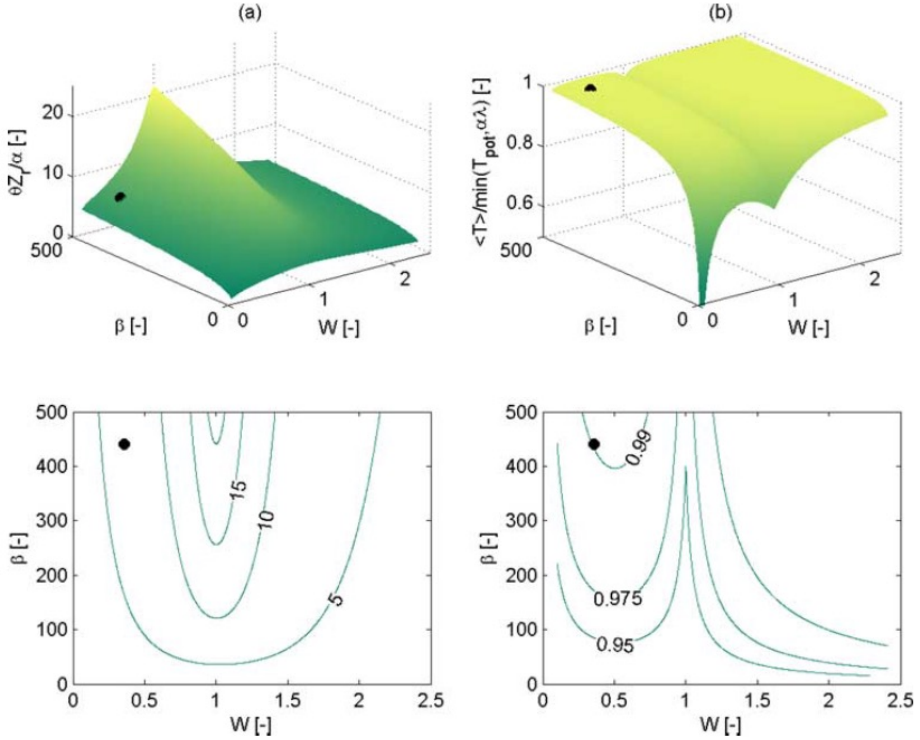




The American School, Optimization
C cost & benefit (Guswa, WRR, 2008
Guswa, WRR, 2010)

$$\frac{Z_r}{\alpha/\theta} = \frac{\ln\left(W\left[1+\frac{1}{2}\beta(1-W)^2 \pm \sqrt{\beta(1-W)^2+\left(\frac{1}{2}\beta(1-W)^2\right)^2}\right]\right)}{(1-W)}$$

$$\beta = \frac{\theta}{\alpha A} = \frac{\theta}{\alpha} \cdot \frac{SRL \cdot WUE}{\gamma_r \cdot RLD} \cdot T_{pot} \cdot f_{seas}$$



Root Distribution Model (2D)

Perona et al., Ecol. Eng. 2022

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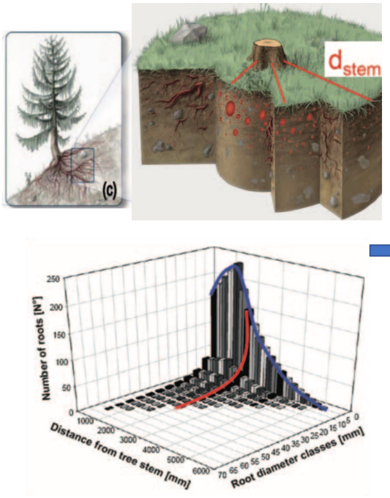
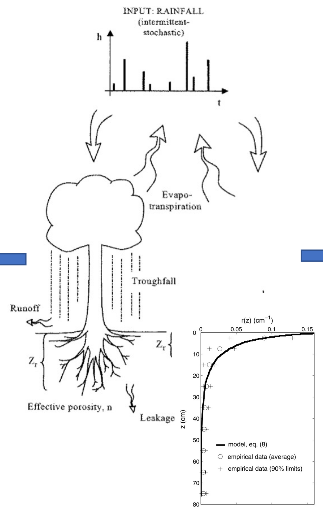
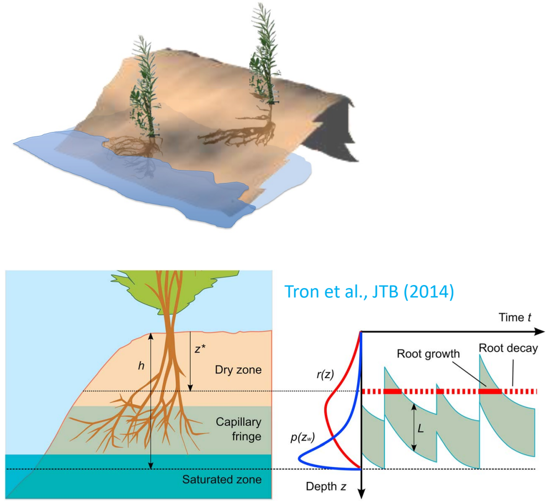
Schwarz et al. 2010

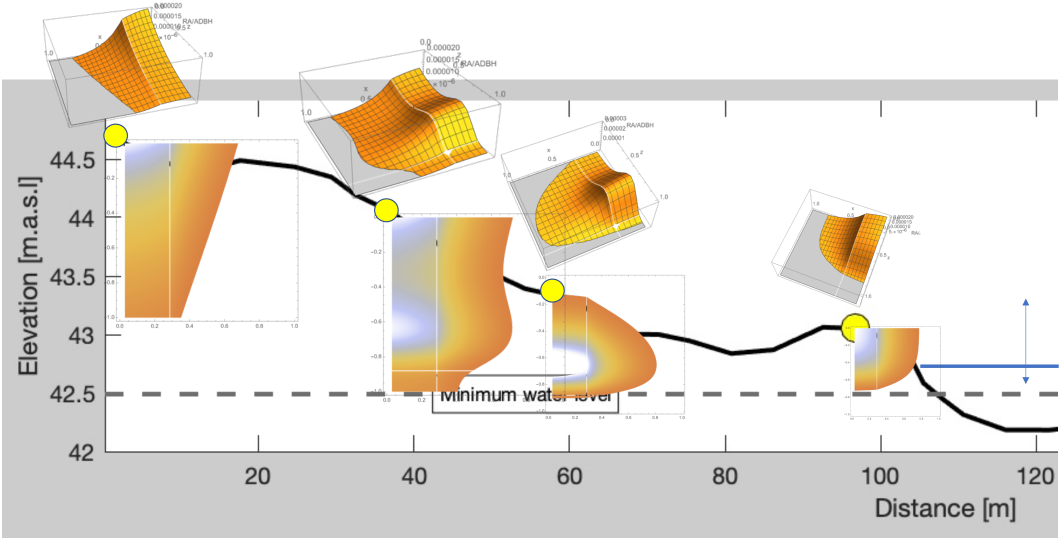


Laio et al. 2006

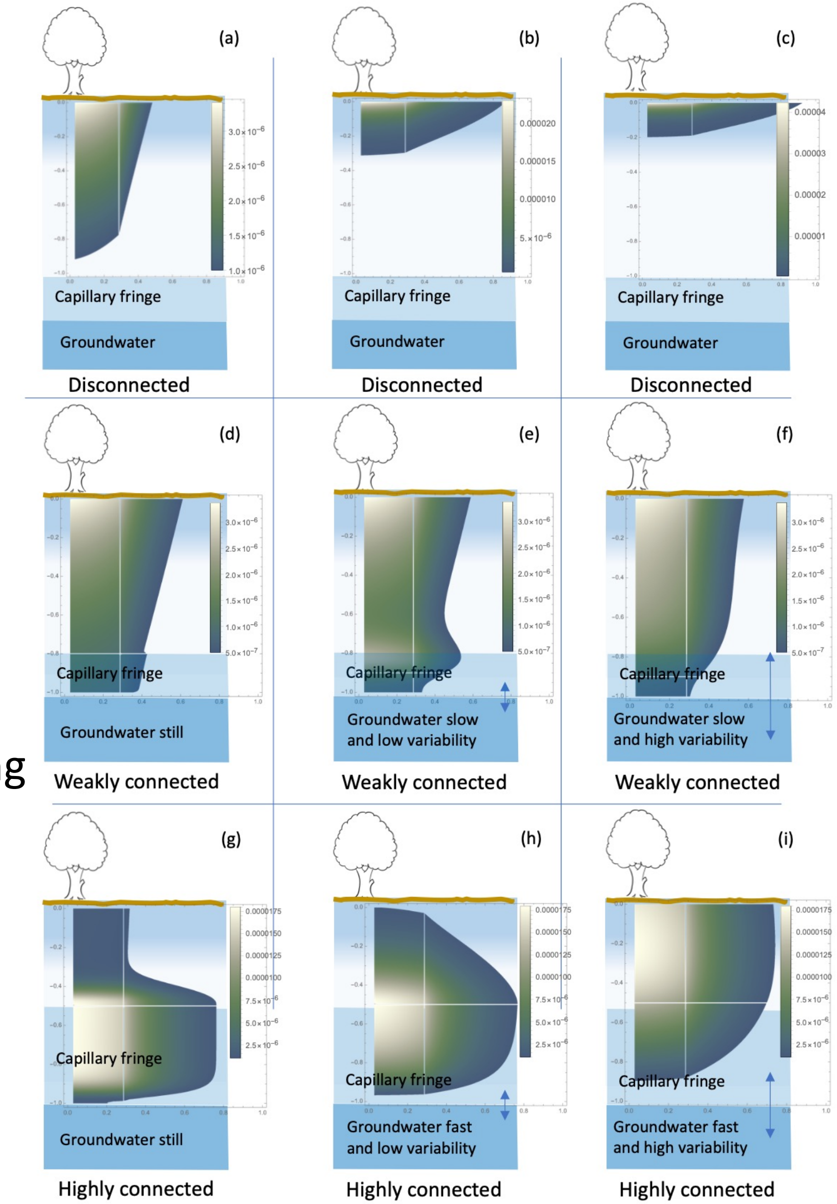


Tron et al. 2014



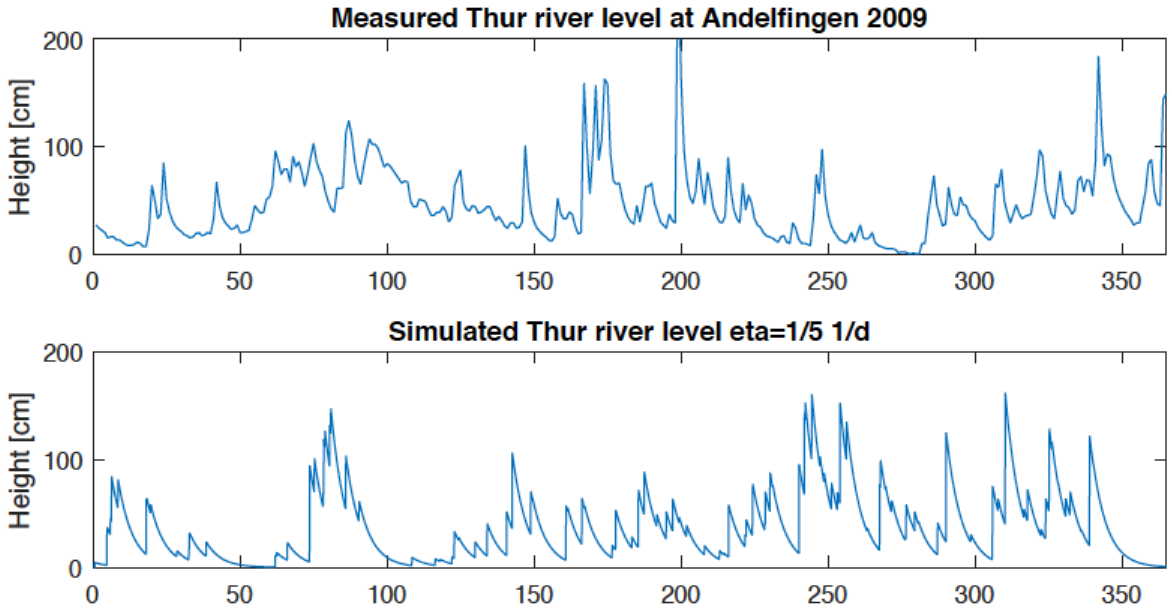


Awaiting for testing to crop plants under different tropism scenarios. Any interest?



A stochastic model for riparian plant roots growth

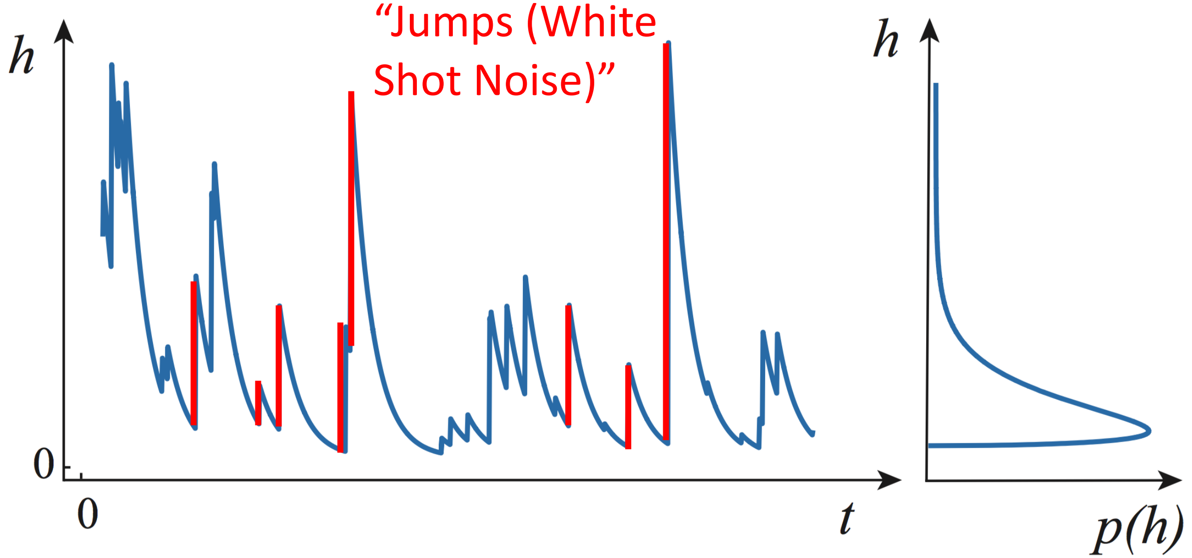
(Tron et al., JTB 2014)



FIRST: approximation of river fluctuations as a stochastic process driven by white shot noise:

Stochastic jumps (Poisson) + deterministic descends

Noise term as "Jumps (White Shot Noise)"



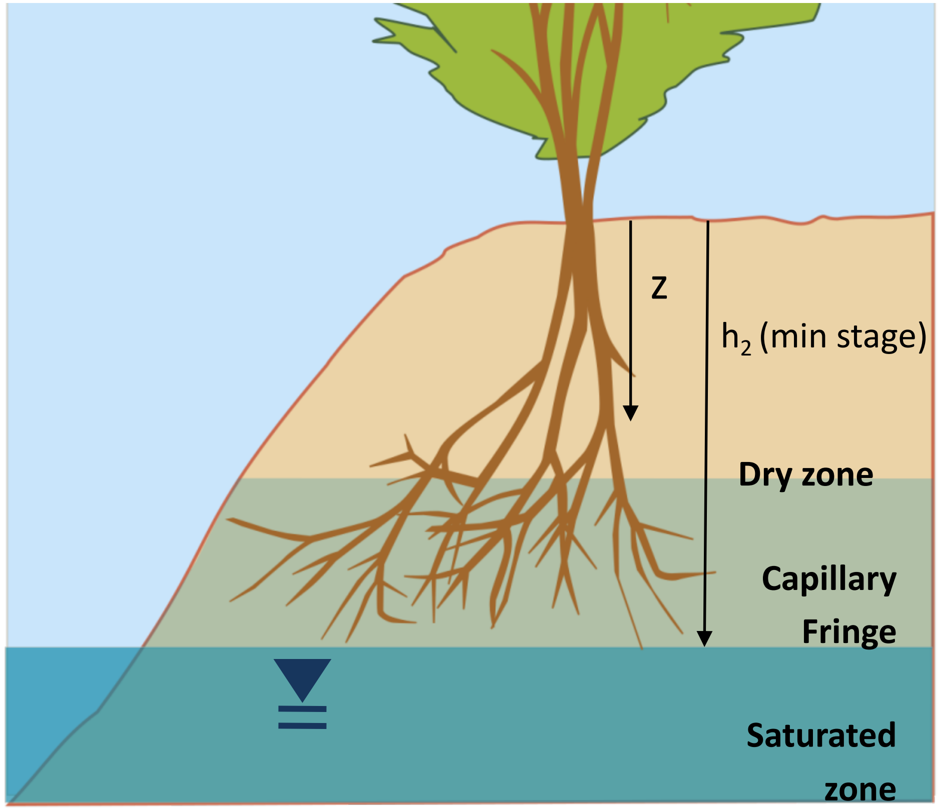
$$\frac{dh}{dt} = -\frac{h}{\tau} + \zeta(t)$$

Compound Poisson Process

Cox and Miller (1969), Iturbe et al. (1999), Ridolfi et al. (2006), Botter et al. (2007)

The pdf p(h) is analytical and is a Gamma function

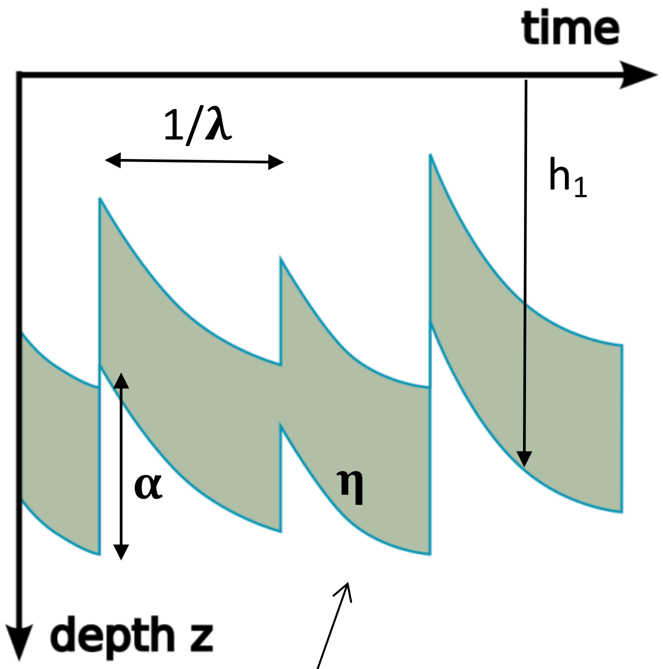
The model is built considering that in riparian environments hydrotropism and aerotropism are the driving mechanisms controlling plant roots growth



One obtains that the pdf of $z_i = \tilde{z}_i/\tilde{h}_2$ is

$$p(z_i) = \frac{\alpha^{-\lambda/\eta}}{\Gamma\left(\frac{\lambda}{\eta}\right)} e^{(z_i - h_1)/\alpha} (h_1 - z_i)^{\lambda/\eta - 1},$$

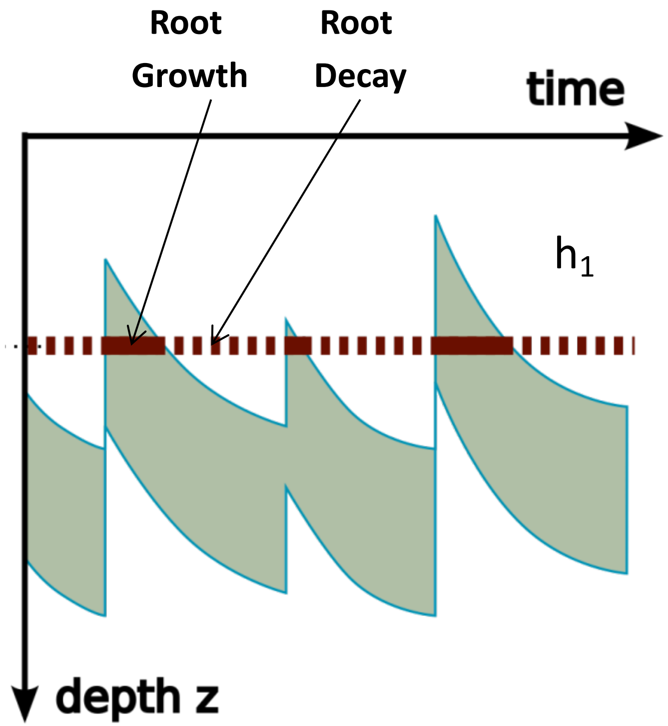
(Ridolfi et al., 2011)



Water table fluctuations

STOCHASTIC PROCESS DRIVEN BY WHITE SHOT NOISE

DICHOTOMOUS NOISE

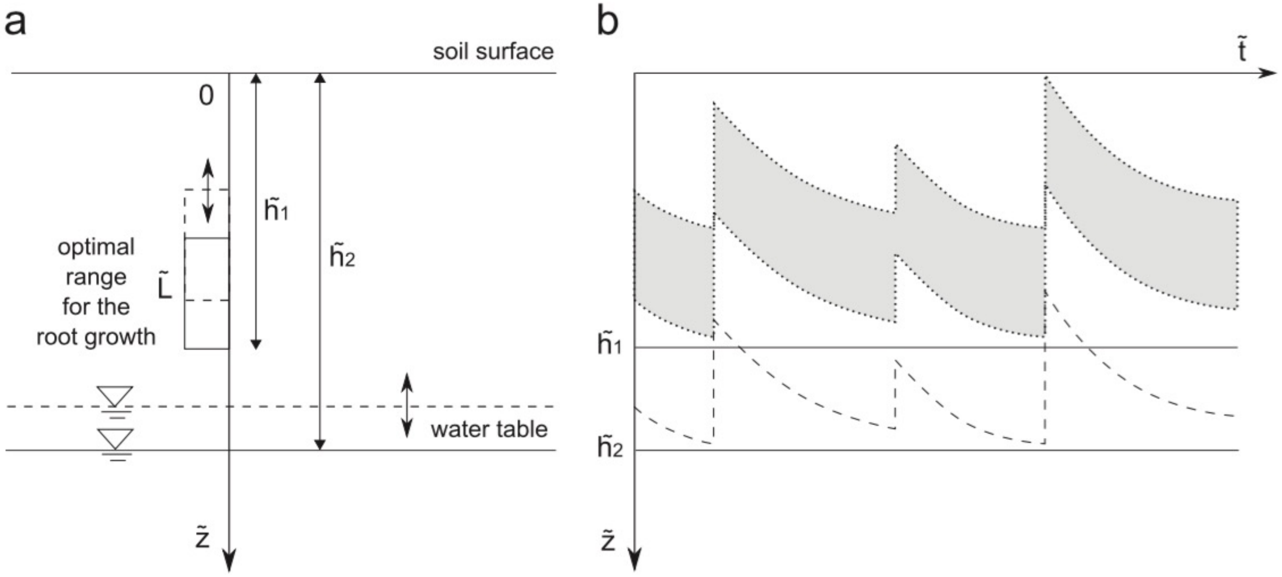


Probability that a depth z is within the zone favourable for root growth

$$k(z) = \int_z^{\min[z+L, h_1]} p(z_i)\, dz_i.$$

$$k(z) = \begin{cases} \dfrac{\Gamma\left(\frac{\lambda}{\eta}, \frac{h_1 - z - L}{\alpha}\right) - \Gamma\left(\frac{\lambda}{\eta}, \frac{h_1 - z}{\alpha}\right)}{\Gamma\left(\frac{\lambda}{\eta}\right)} & \text{if } -\infty < z < h_1 - L, \\ 1 - \dfrac{\Gamma\left(\frac{\lambda}{\eta}, \frac{h_1 - z}{\alpha}\right)}{\Gamma\left(\frac{\lambda}{\eta}\right)} & \text{if } h_1 - L < z < h_1, \end{cases}$$

Dichotomous process for root growth and death



The telegraph process

$$\frac{\mathrm{d}r(z)}{\mathrm{d}\tilde{t}}=\begin{cases}\tilde{f}_1(r(z))=\beta(z)(1-r(z)) & \text{if } z_i-L<z<z_i,\\ \tilde{f}_2(r(z))=-\gamma r(z) & \text{if } z<z_i-L \;\vee\; z>z_i,\end{cases}$$

→

$$\frac{\mathrm{d}r(z)}{\mathrm{d}t}=\begin{cases}f_1(r(z))=\theta(z)(1-r(z)) & \text{if } z_i-L<z<z_i,\\ f_2(r(z))=-r(z) & \text{if } z<z_i-L \;\vee\; z>z_i,\end{cases}$$

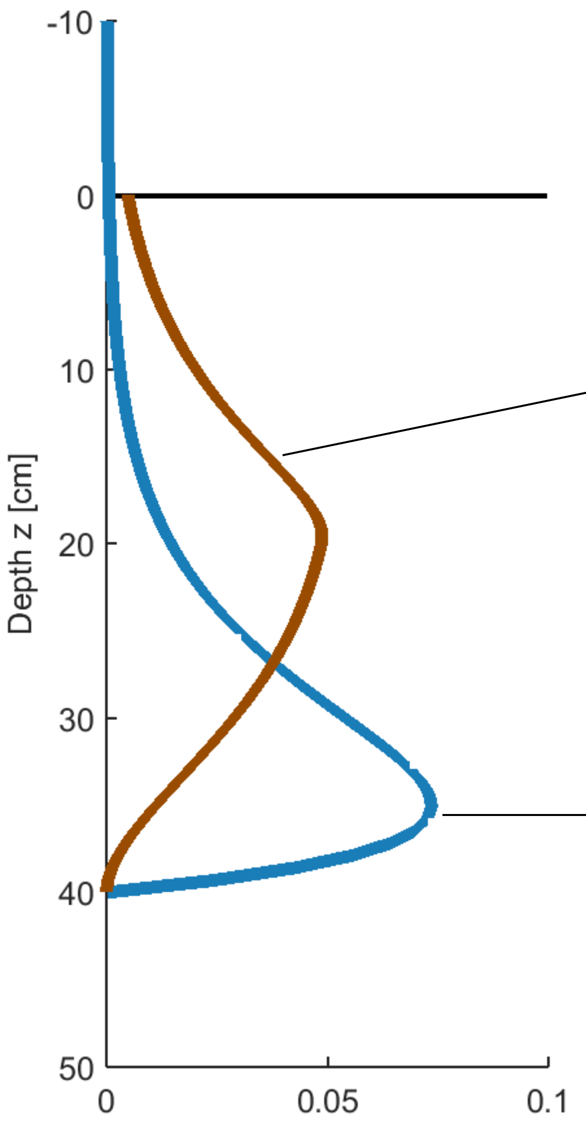
The dichotomous process is a stochastic process forced by the dichotomous noise ξ_{dn} which can assume only two values, Δ_1 and Δ_2, with transition rate k_2 for the transition Δ_2-Δ_1, and k_1 1⁄4 1 k_2 for Δ_1-Δ_2.

$$p(r(z))=\frac{\Gamma\left(\frac{1}{\theta(z)}-\frac{k(z)}{\theta(z)}+k(z)+1\right)}{\Gamma(k(z))\Gamma\left(\frac{1}{\theta(z)}-\frac{k(z)}{\theta(z)}\right)}(r(z)+\theta(z)(1-r(z)))$$
$$\times(1-r(z))^{(1/\theta(z))(1-k(z))-1}r(z)^{k(z)-1},$$

Pdf of root density at a given depth, z

Tron et al., 2014

This is the first model for root growth that has an analytical solution for the vertical profile (not a pdf!) of the biomass.



ROOT PROFILE r(z) is the mean of p(r(z)) at given z

$$\bar{r}(z) = \int_0^1 r(z) \cdot p(r(z))\, \mathrm{d}r = \frac{2\theta(z)k(z)}{\theta(z)+\theta(z)k(z)+1-k(z)}.$$

$$k(z) = \begin{cases} \left[\Gamma\left(\tilde{\lambda}, \frac{h-z-L}{\alpha}\right) - \Gamma\left(\tilde{\lambda}, \frac{h-z}{\alpha}\right)\right] \cdot \Gamma\left(\tilde{\lambda}\right)^{-1} & \text{if } -\infty < z < h-L, \\ 1 - \Gamma\left(\tilde{\lambda}, \frac{h-z}{\alpha}\right) \cdot \Gamma\left(\tilde{\lambda}\right)^{-1} & \text{if } h-L < z < h, \end{cases}$$

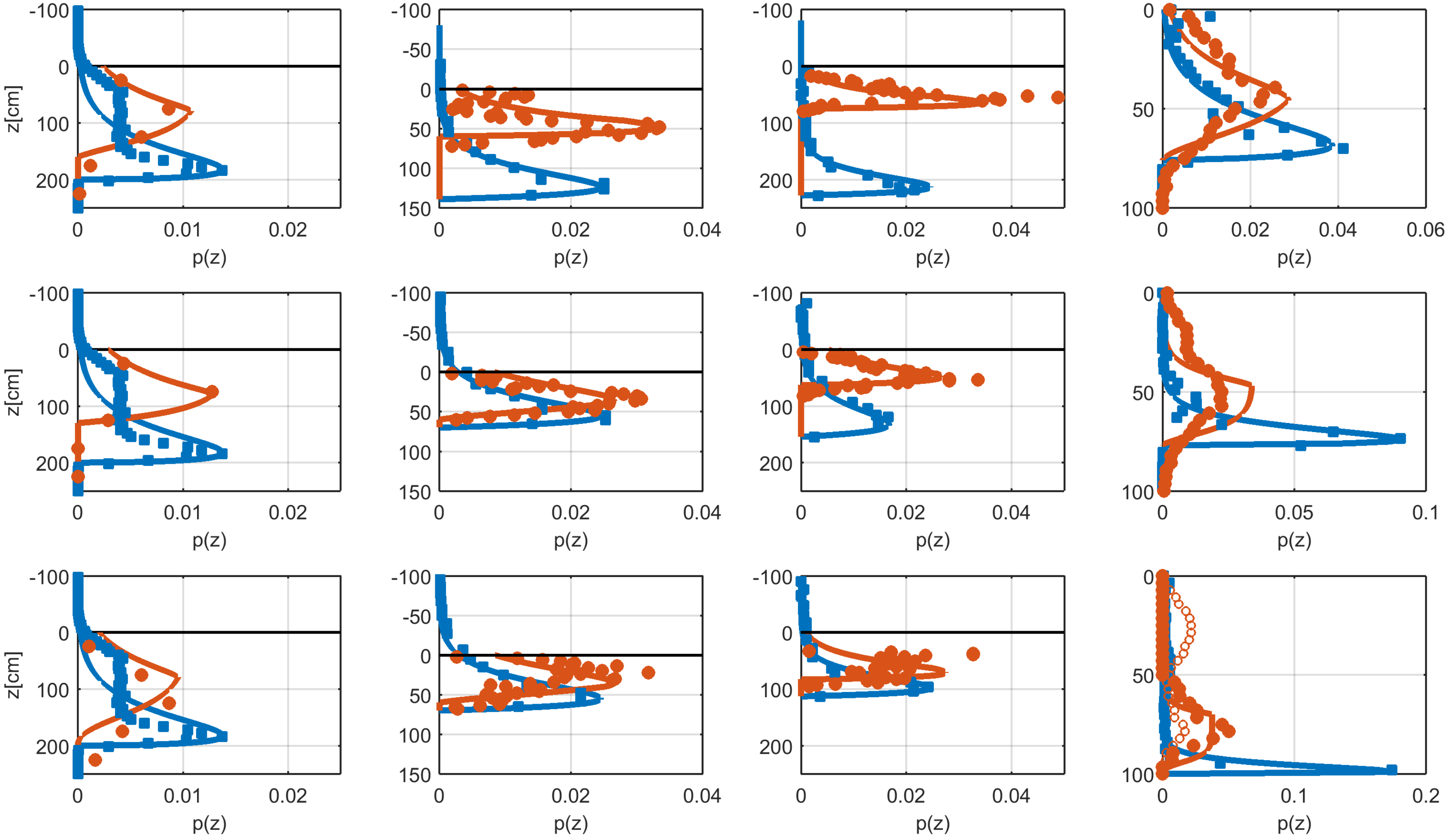
PDF of the WATER TABLE p(z)

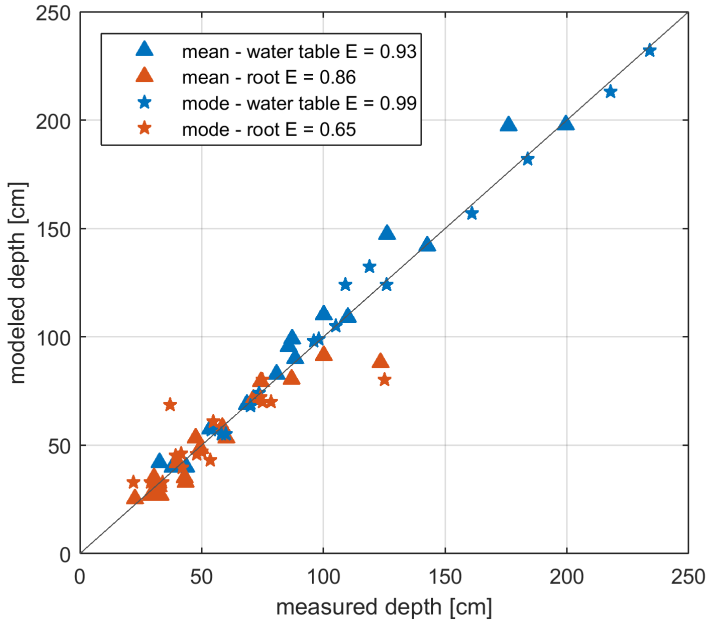
$$p(z) = \frac{-\tilde{\lambda}}{\Gamma\left(\tilde{\lambda}\right)} e^{\frac{z-h}{\alpha}} (h-z)^{\tilde{\lambda}-1}$$

Model validation

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

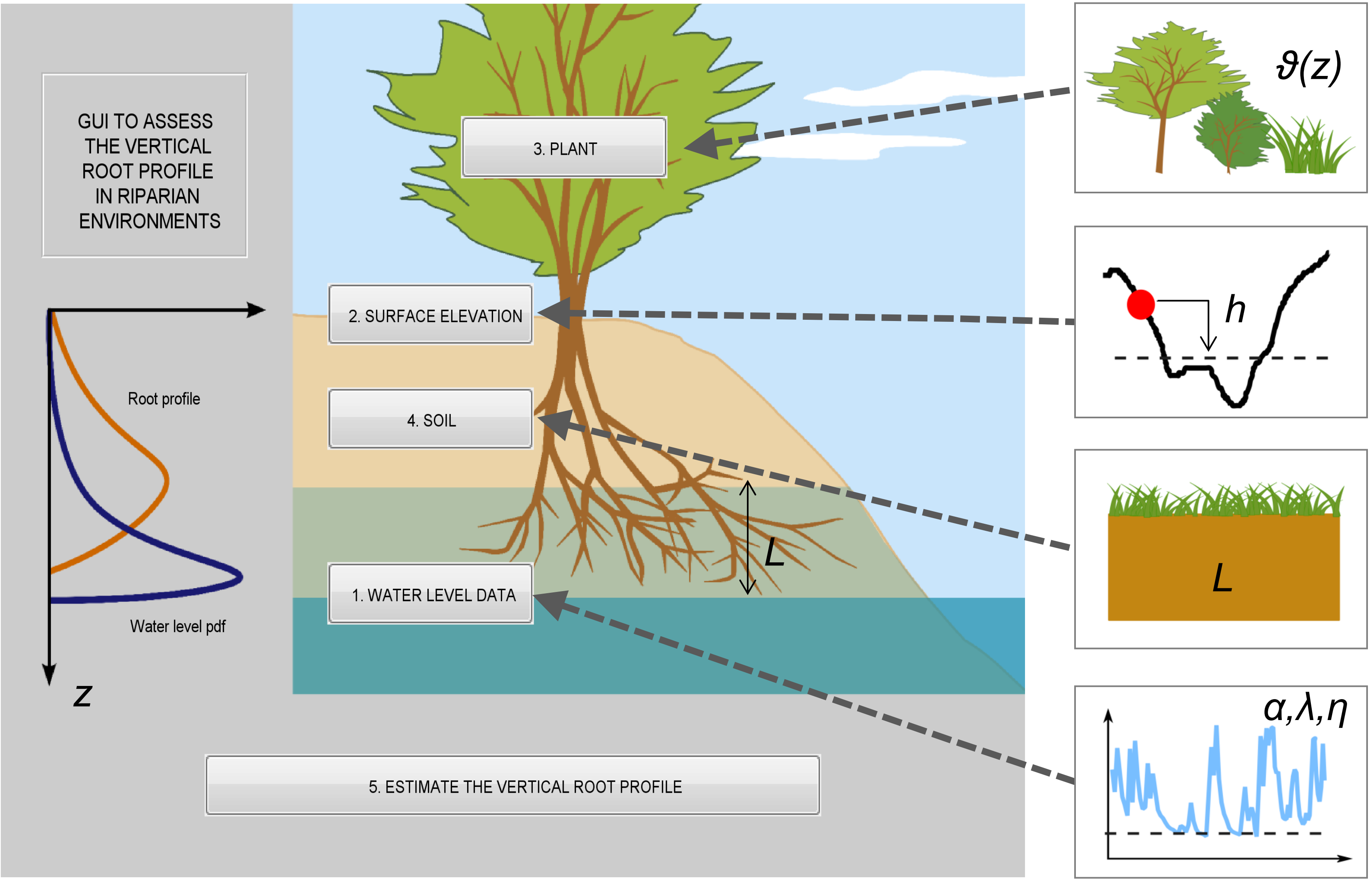
1. Rhone riverbank **2. Thur river island** **3. EPFL experiment**



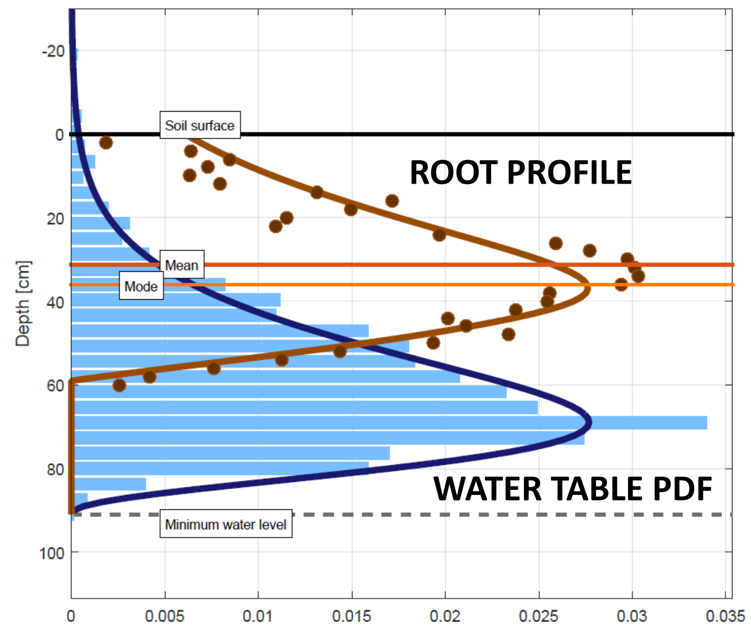


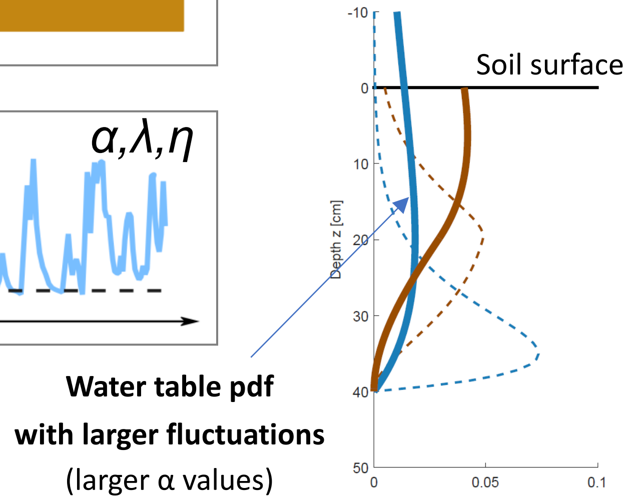
details in Tron, Perona et al. (2015) Geophysical Research Letters

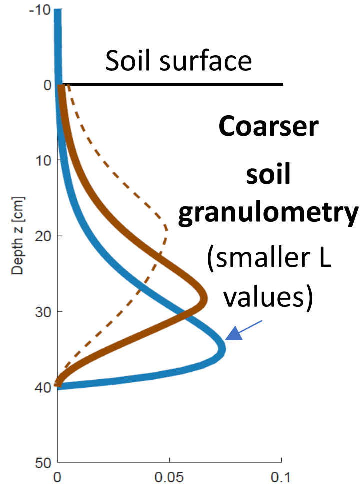
Root development graphical User Interface



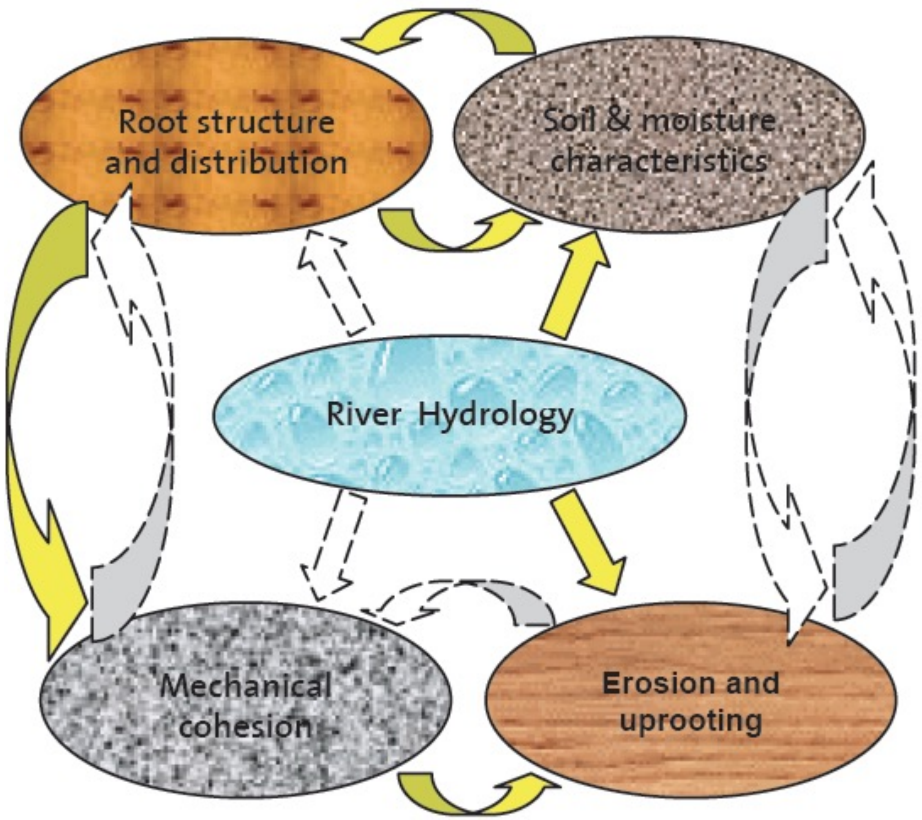
GUI RESULTS







Some first conclusions



Growing roots at high elevations might be worth not only because floods come less frequently (hydrological return time): the deeper the roots are, the higher the actual return time of the flooding event that uproots the plant (continue…)