Concepts of tree growth and biomechanics

that could be considered in future models of tree stability

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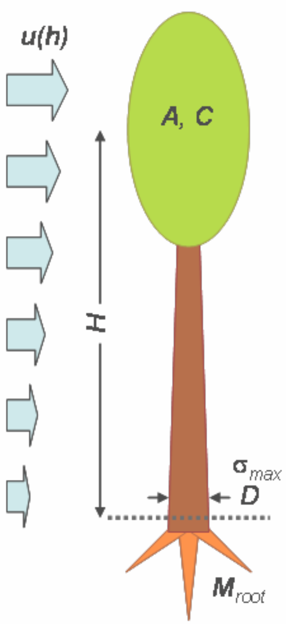
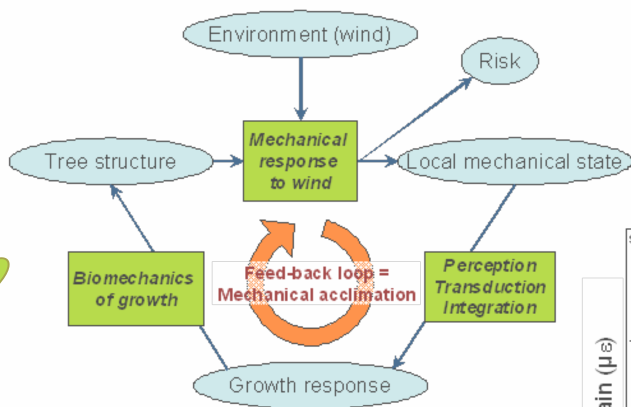
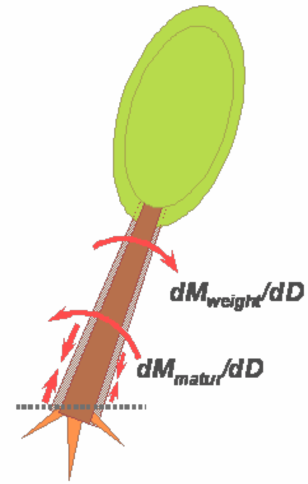
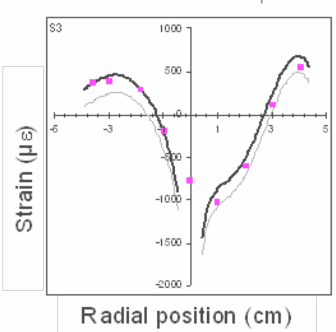


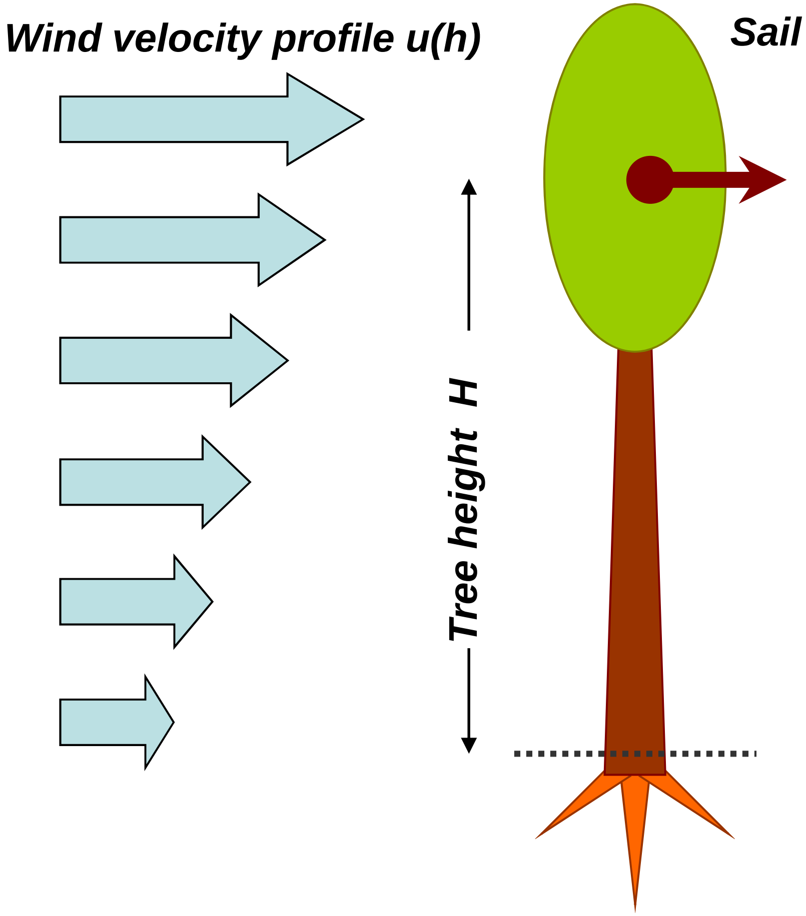






Tree biomechanics and tree stability

Mechanical stability of a tree submitted to wind



Sail area A + Drag coefficient C

Drag force $F \sim A.C.u_H^2$

Bending moment $M_{wind} = F.H \sim H.A.C.u_H^2$

$M_{dynamic} = k_{dyn}.M_{static}$

Dynamic effects increase apparent load

Sellier and Fourcaud (2009) Am. J. Bot.

Sellier et al. (2008) Forestry

Tree biomechanics and tree stability

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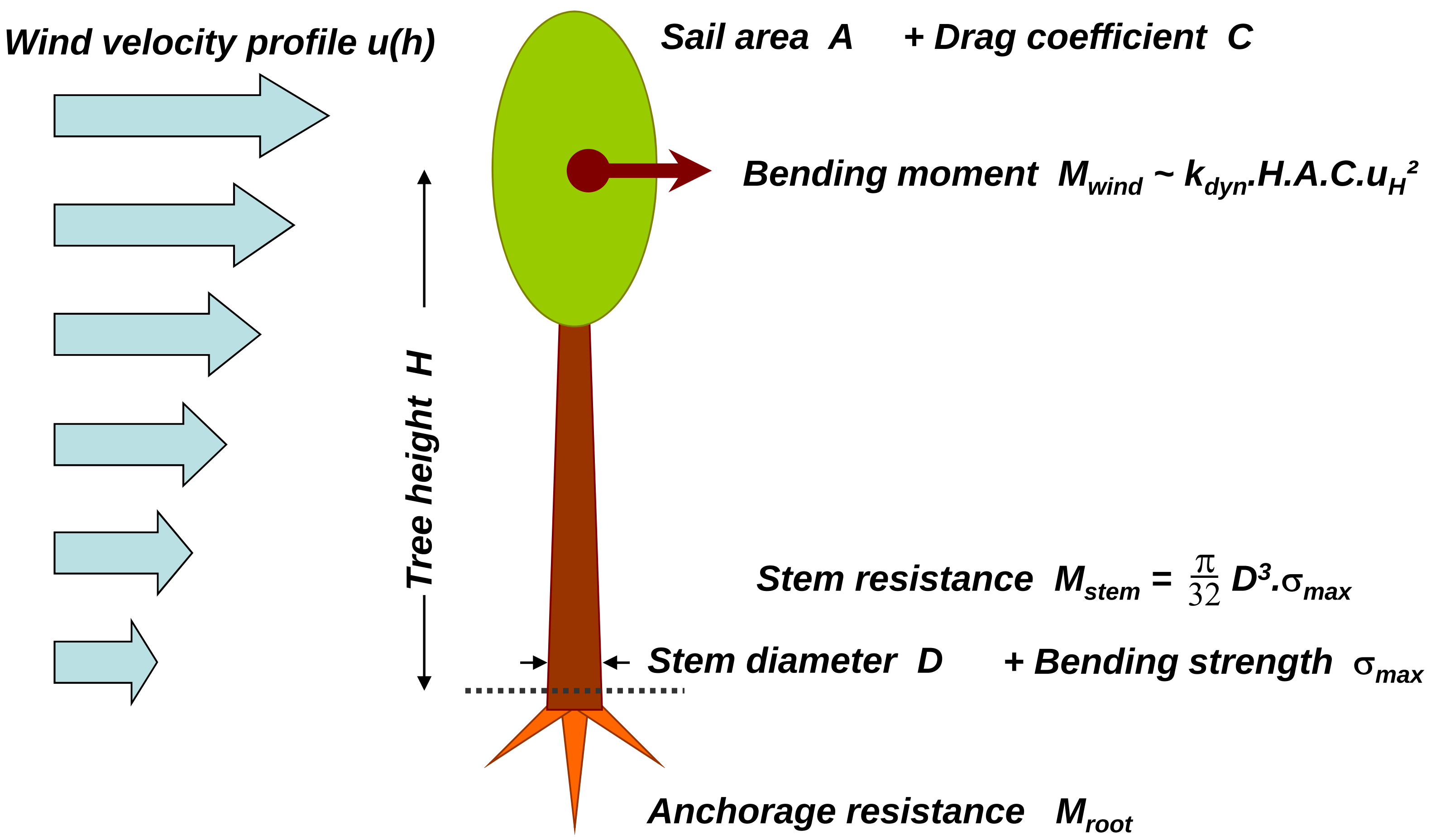
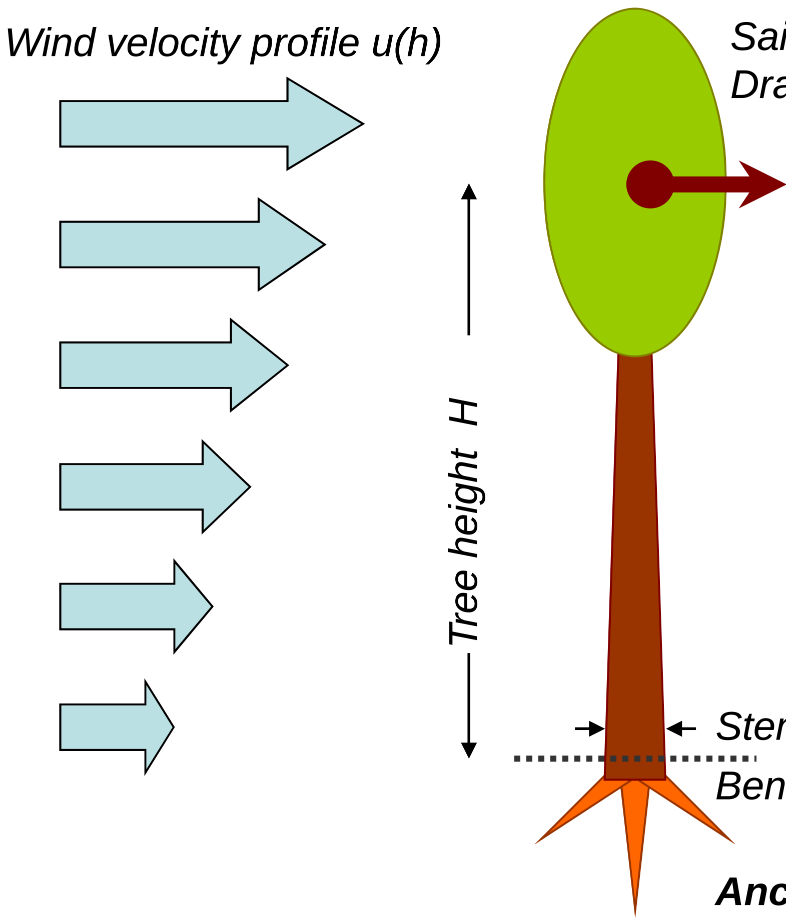


Tree biomechanics and tree stability

Mechanical stability of a tree submitted to wind



Sail area A

Drag coefficient C

Bending moment $M_{wind} \sim k_{dyn}.H.A.C.u_H^2$

Failure if $M_{wind} > \min(M_{stem}, M_{root})$

'Risk' $\sim \dfrac{k_{dyn}.H.A.C.u_H^2}{\min(M_{root}, \frac{\pi}{32} D^3.\sigma_{max})}$

Stem resistance $M_{stem} = \frac{\pi}{32} D^3.\sigma_{max}$

Stem diameter D

Bending strength σ_{max}

Anchorage resistance M_{root}

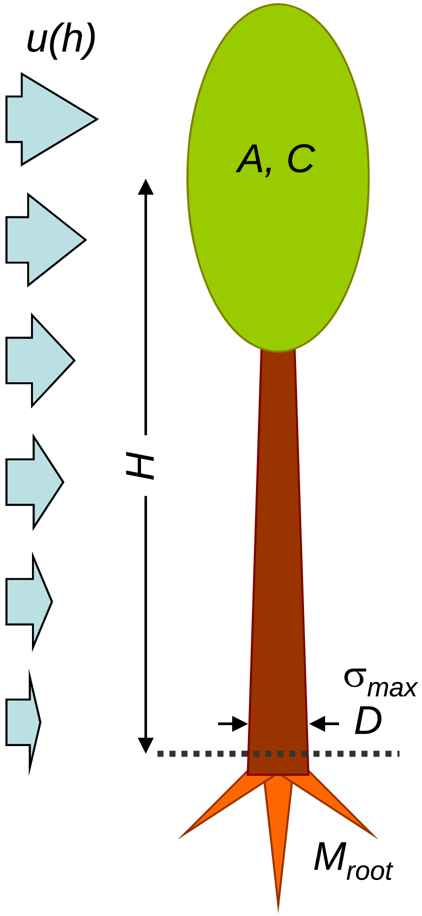
Tree biomechanics and tree stability

Mechanical stability of a tree submitted to wind

- "Conventional" mechanical problem:
  - solicitation is much quicker than plant growth reaction
  - no direct coupling between mechanics and growth
- Growth plays a role before and after the wind event:
  - before = **mechanical acclimation** through:
    - allocation : roots / stem H / stem D / crown (thigmomorphogenesis)
    - crown architecture : shape and branching pattern
    - tree posture : stem and branch angles (tropisms)
    - bending strength: wood quality, growth stress
  - after = **restoration of the stem orientation** (if limited damages)

Mechanical Acclimation of the Tree

Growth allocation and Thigmomorphogenesis



Perception of moderate winds

- Perceived signal: strains

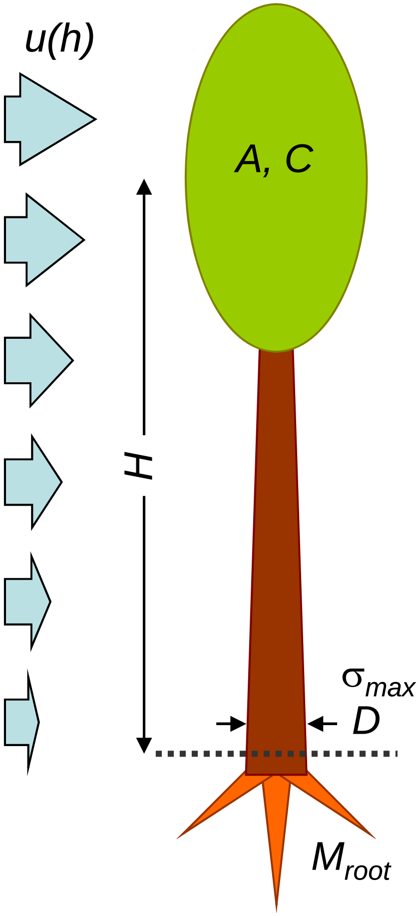
  Coutand and Moulia (2000) ***J. Exp. Bot.***

- Integration of the signal in time and space…

⇒ Can be computed by dynamic models

Mechanical Acclimation of the Tree

Growth allocation and Thigmomorphogenesis

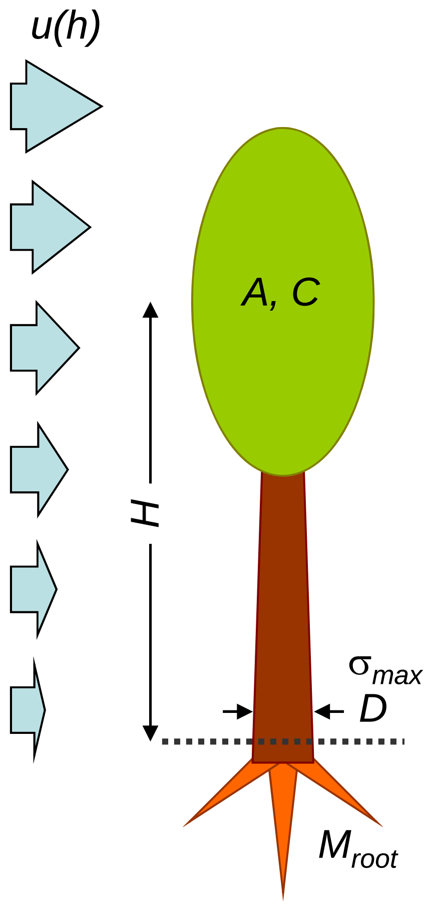


Typical response to repeated winds:

$$\text{Risk} \sim \frac{k_{dyn}.H.A.C.u_H^2}{\min\left(M_{root}, \frac{\pi}{32}D^3.\sigma_{max}\right)}$$

Mechanical Acclimation of the Tree

Growth allocation and Thigmomorphogenesis



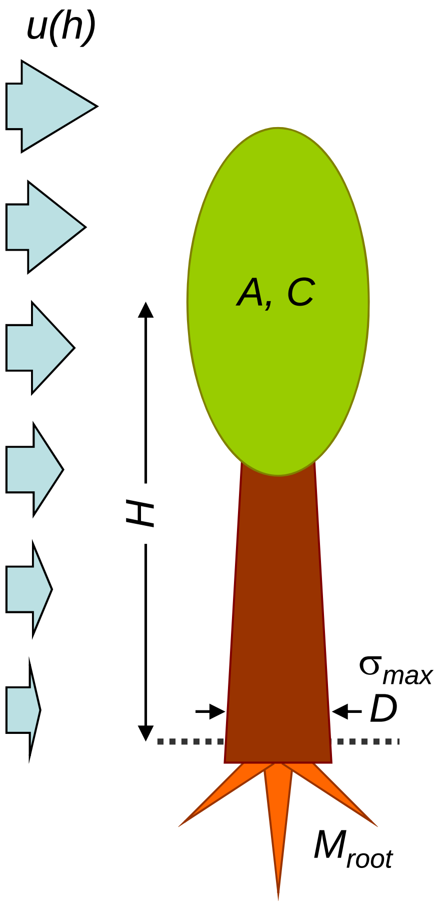
Typical response to repeated winds:

- Reduced height growth

$$\text{Risk} \sim \frac{k_{dyn}.H.A.C.u_H^2}{\min\left(M_{root}, \frac{\pi}{32}D^3.\sigma_{max}\right)}$$

Mechanical Acclimation of the Tree

Growth allocation and Thigmomorphogenesis



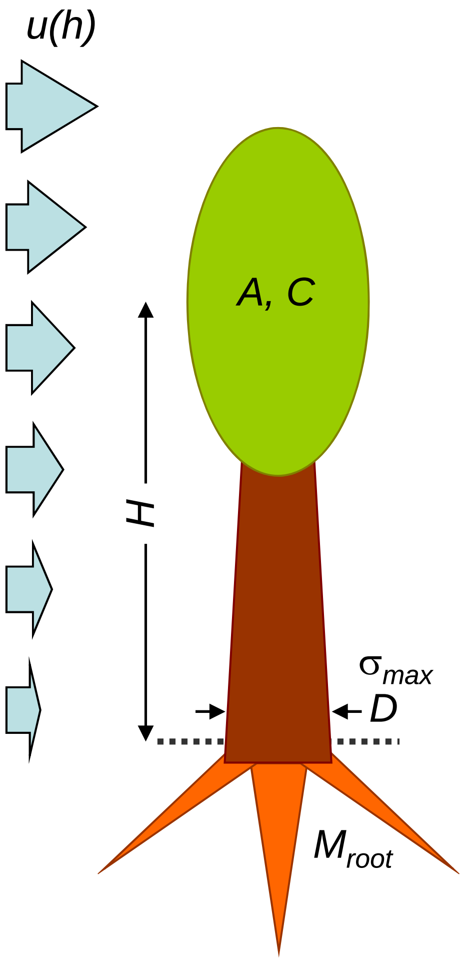
Typical response to repeated winds:

- Reduced height growth
- Increased diameter growth

$$\textbf{Risk} \sim \frac{k_{dyn}.H.A.C.u_H^2}{\min(M_{root}, \frac{\pi}{32}D^3.\sigma_{max})}$$

Mechanical Acclimation of the Tree

Growth allocation and Thigmomorphogenesis



Typical response to repeated winds:

- Reduced height growth
- Increased diameter growth
- Increased root growth

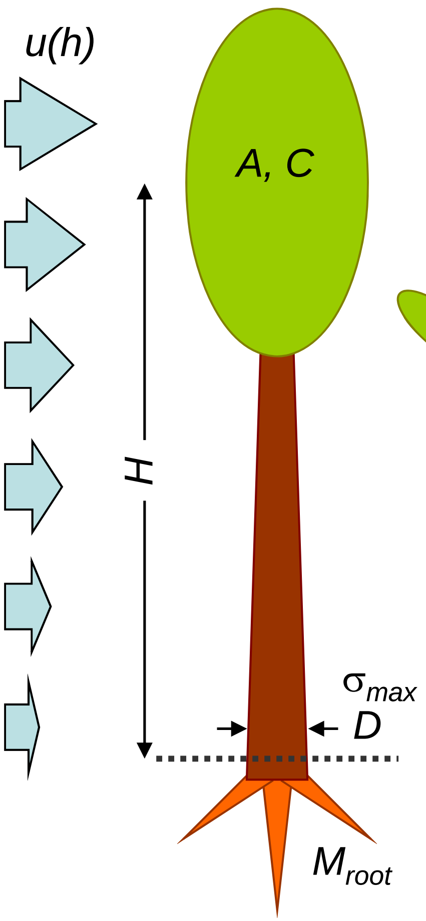
$$\text{Risk} \sim \frac{k_{dyn}.H.A.C.u_H^2}{\min\left(M_{root}, \frac{\pi}{32}D^3.\sigma_{max}\right)}$$

Mechanical Acclimation of the Tree

Crown architecture

Sellier et al. (2006) Tree physiol.

Sellier and Fourcaud (2009) Am. J. Bot.



Branching pattern

Branch angle

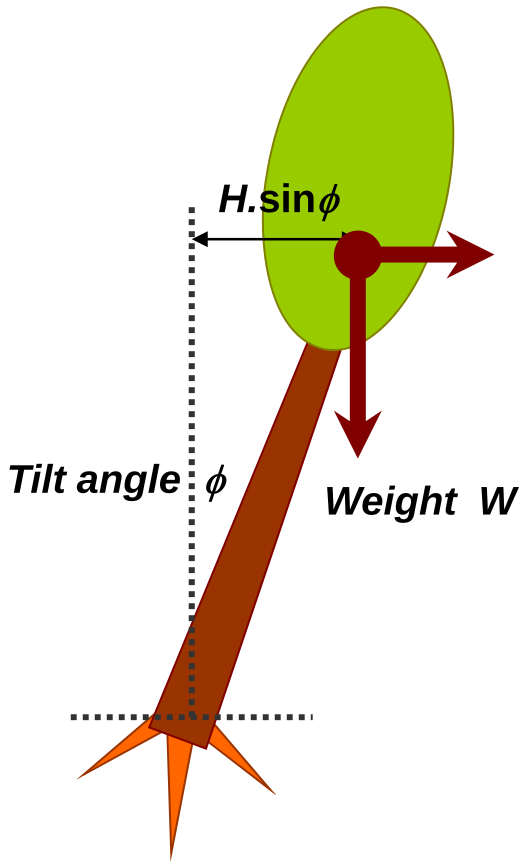
Branch size distribution

Crown shape

$$\textbf{Risk} \sim \frac{k_{dyn}.H.A.C.u_H^2}{\min(M_{root}, \frac{\pi}{32} D^3.\sigma_{max})}$$

Control of tree posture

Influence of stem angle on mechanical stability



Tilt angle makes bending under the self-weight

Bending moment $M_{total} = M_{wind} + M_{weight}$

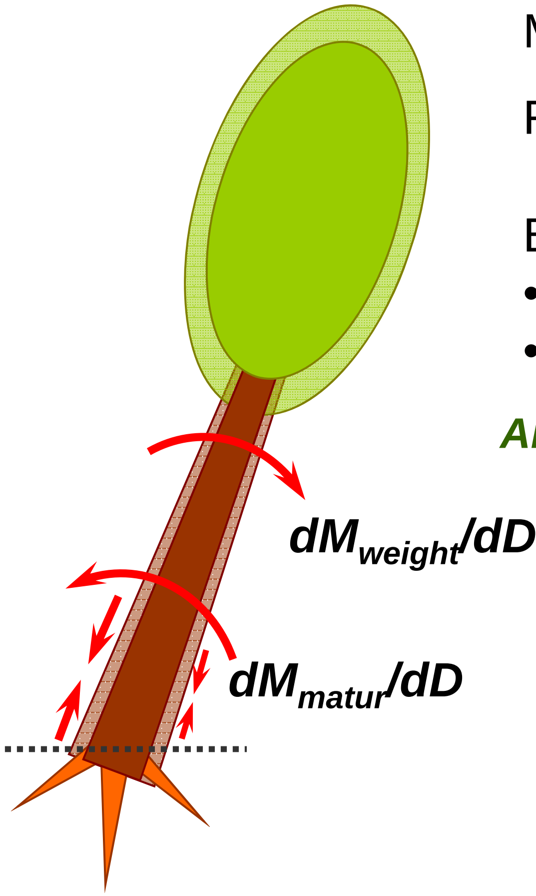
Weight moment $M_{weight} = W.H.\sin\phi$

$$\text{Risk} \sim \frac{k_{dyn}.H.\cos\phi.A.C.u_H^2 + W.H.\sin\phi}{\min(M_{root}, \frac{\pi}{32}D^3.\sigma_{max})}$$

- ➢ Asymmetric response to wind
- ➢ Effect on dynamic behavior ?

Control of tree posture

Regulation of stem shape : Tropisms



Mechanism: asymmetric maturation stress

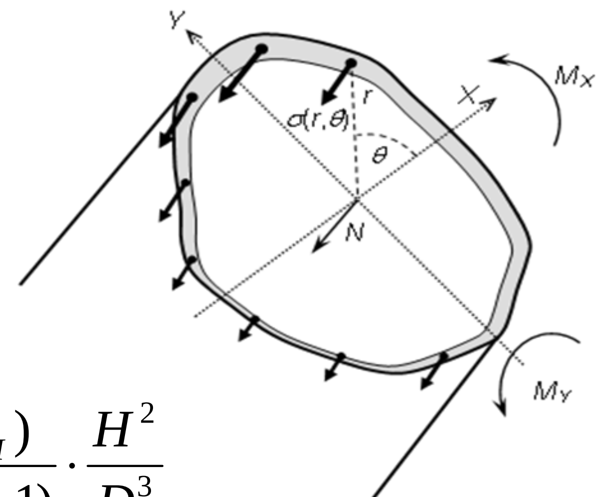
Related to diameter growth (reaction wood)

Balance between the effect of :
- Increase in weight
- Wood maturation

Alméras et al. (2009) J. Theor. Biol.

$$\frac{dC_Y^{matur}}{dD} = -4 \cdot \frac{\Delta\alpha \cdot f \cdot \overline{E} / E}{D^2}$$

$$\frac{dC_Y^{weight}}{dD} = 32g \, \frac{L \cdot \sin\phi \cdot (1 + b_H)}{E \cdot (m+1) \cdot (2n+1)} \cdot \frac{H^2}{D_0^3}$$

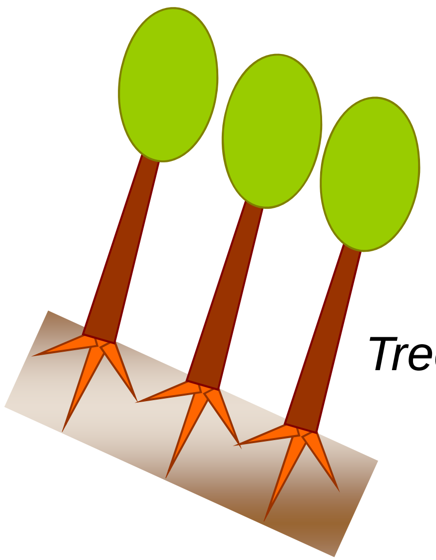


Control of tree posture

Regulation of stem shape : Tropisms

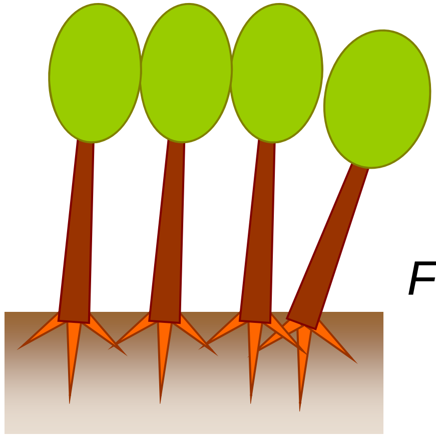
Situations of “equilibrium” tilt angle

Involves a gravitropic reaction



Trees on slopes

Competition between phototropism and gravitropism

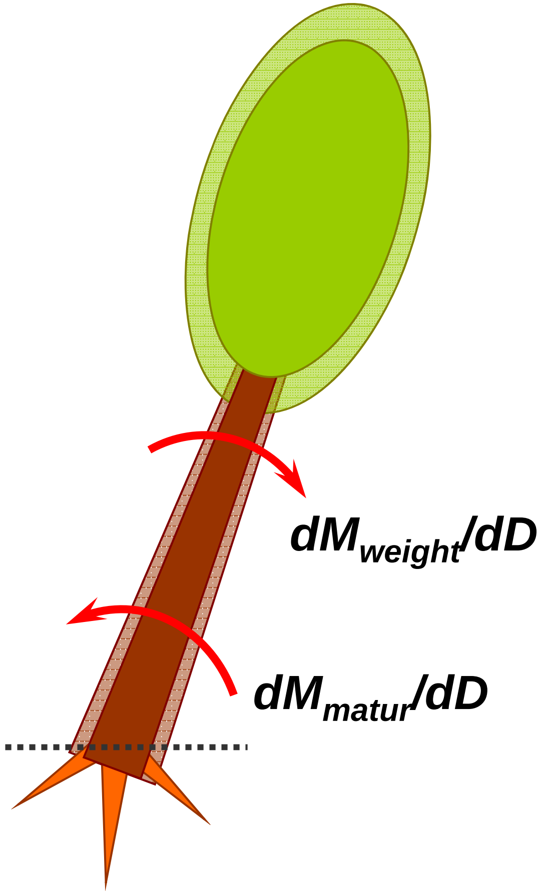


Forest edges

Optimal light interception at the cost of mechanical stability

Control of tree posture

Restoration of stem shape/angle



After moderate tree damages:

- Permanent strains due to wood failure
- Partial up-rooting

Restoration by gravitropic up-righting
Coupled with growth

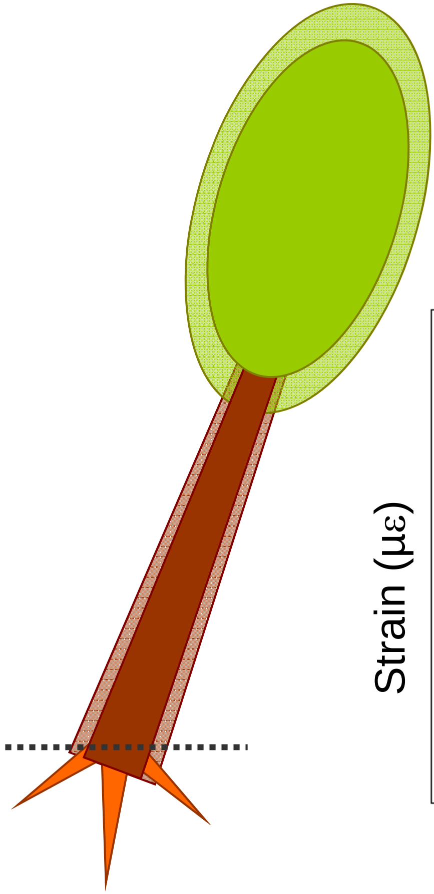
Limitations to gravitropism

$$\sin \phi_{\max} = \frac{\overline{E} \cdot \Delta\alpha \cdot f \cdot (m+1) \cdot (2n+1) \cdot D}{12 g \cdot L \cdot H^2}$$

Alméras et al. (2009) J. Theor. Biol.

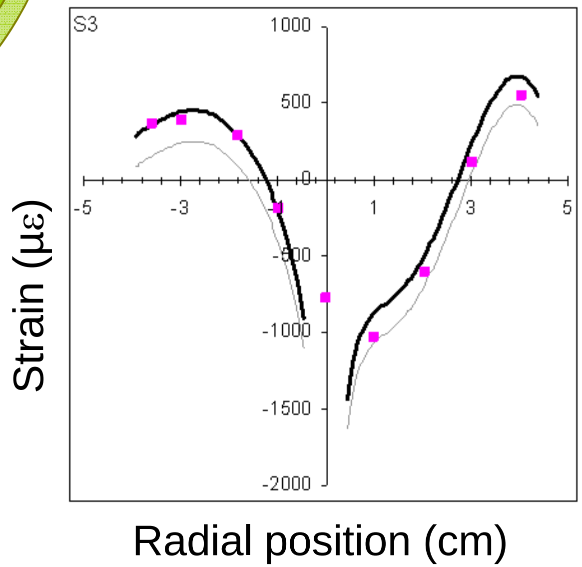
Control of tree posture

Restoration of stem shape/angle



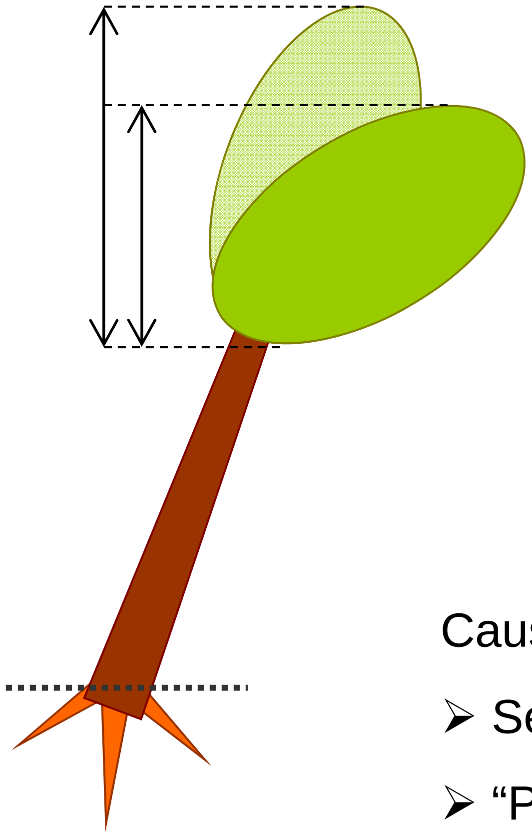
Consequences of gravitropism on forest products:

- Stem shape
- Wood heterogeneity
- High growth stress



Control of tree posture

Influence of dominant wind on tree shape



'Flag' shape = mechanical acclimation of crown shape to wind exposure

Reduction in sail area

$$\text{Risk} \sim \frac{k_{dyn}.H.\cos\phi.A.C.u_H^2 + W.H.\sin\phi}{\min(M_{root}, \frac{\pi}{32}D^3.\sigma_{max})}$$

Cause of this shape?

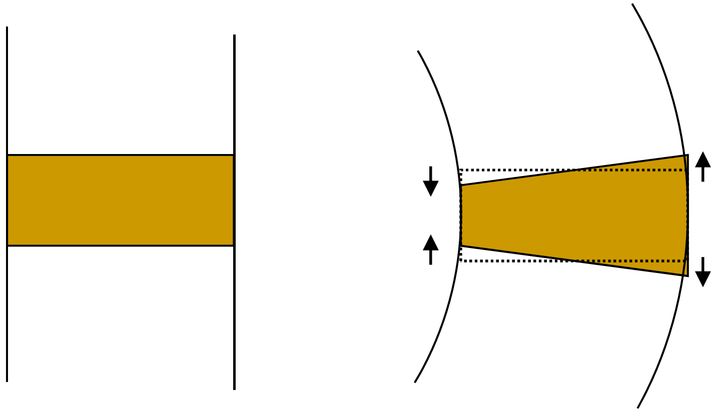
- Selective meristem death?
- "Passive" effect of wind: lignification in bent position?
- "Active" bending through reaction wood?

Bending strength of stems

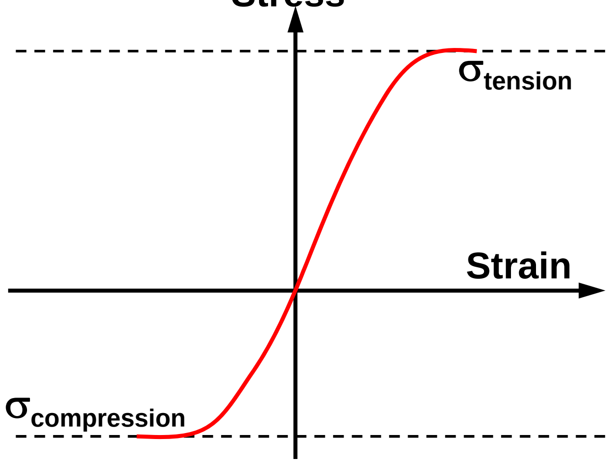
Compressive and tensile strength of wood

Bending is a symmetric action

= tension + compression



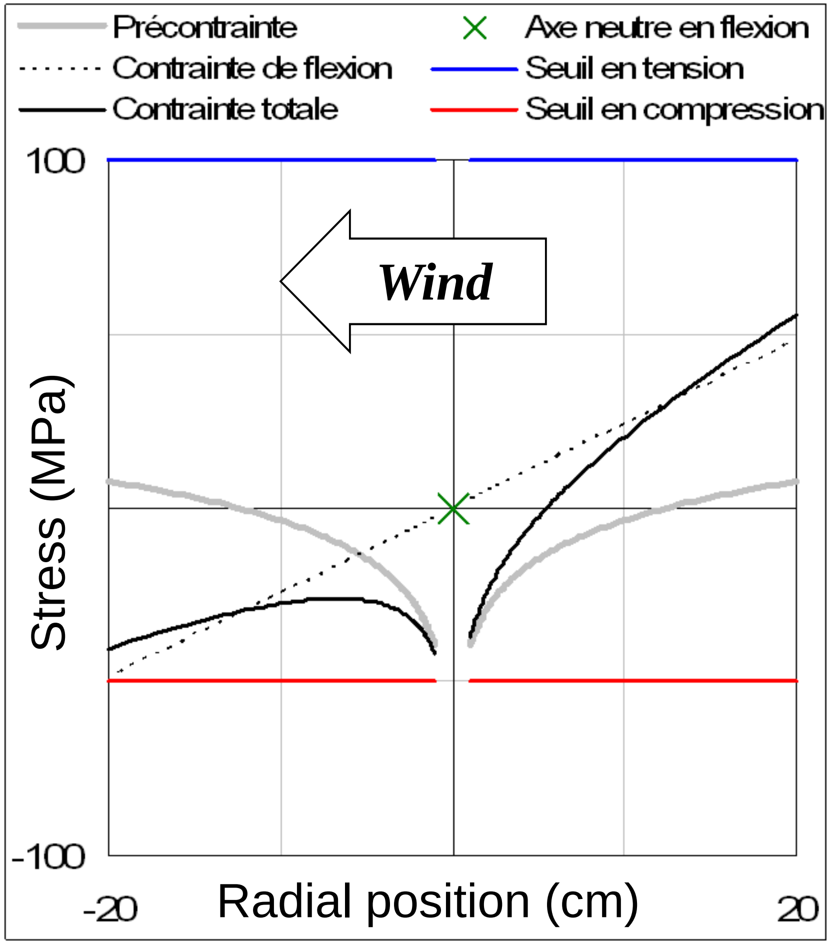
Wood is weaker in compression than in tension



$\Rightarrow$ **Bending strength is mainly related to compressive strength**

Bending strength of stems

Effect of peripheral maturation stress



Alméras et al. (2009) ***Rev. For. Fr.***

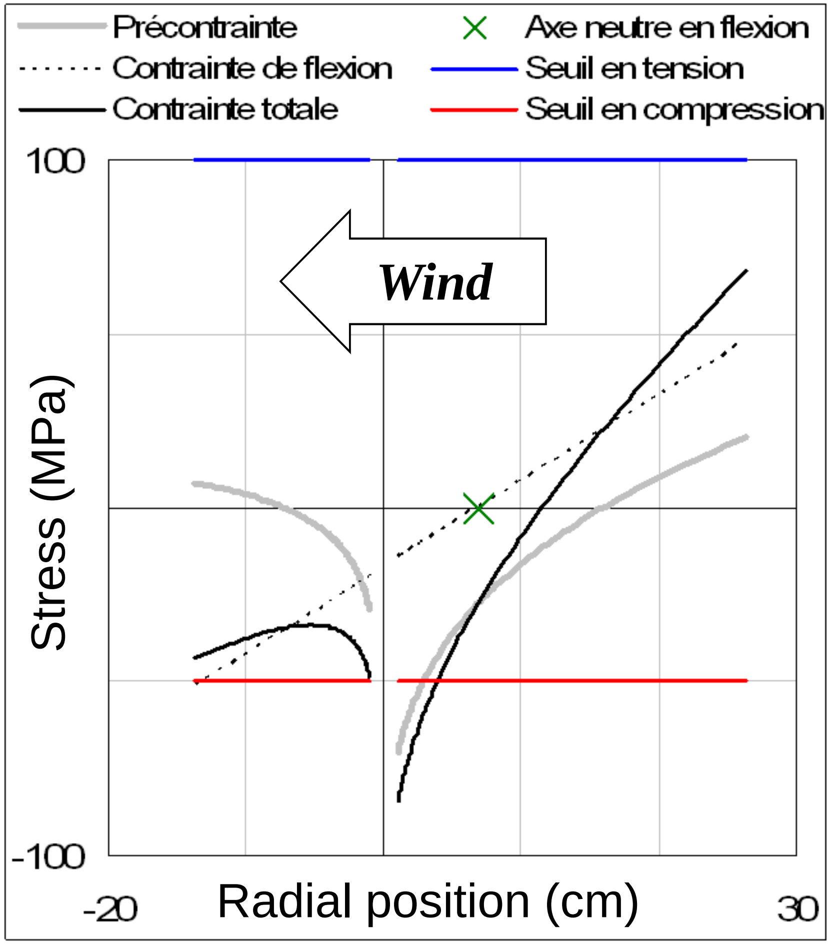
Peripheral tension improves stem strength (+5-50 MPa)

$$\text{Risk} \sim \frac{k_{dyn}.H.A.C.u_H^2}{\min(M_{root}, \frac{\pi}{32}D^3\sigma_{stem})}$$

Bending strength: $\sigma_{stem} = \sigma_{wood} + \sigma_{matur}$

Bending strength of stems

Effect of internal growth stress



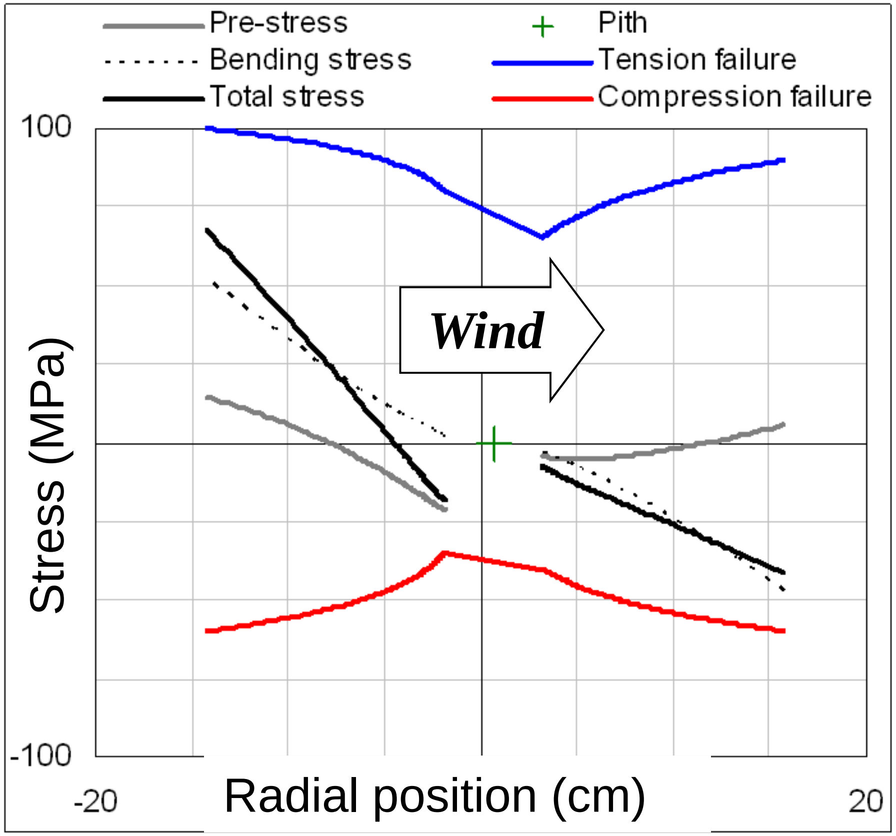
Alméras et al. (2009) ***Rev. For. Fr.***

Internal compression may weaken the stem if associated to eccentricity

Strength depends on wind direction!

Bending strength of stems

Variations in wood quality



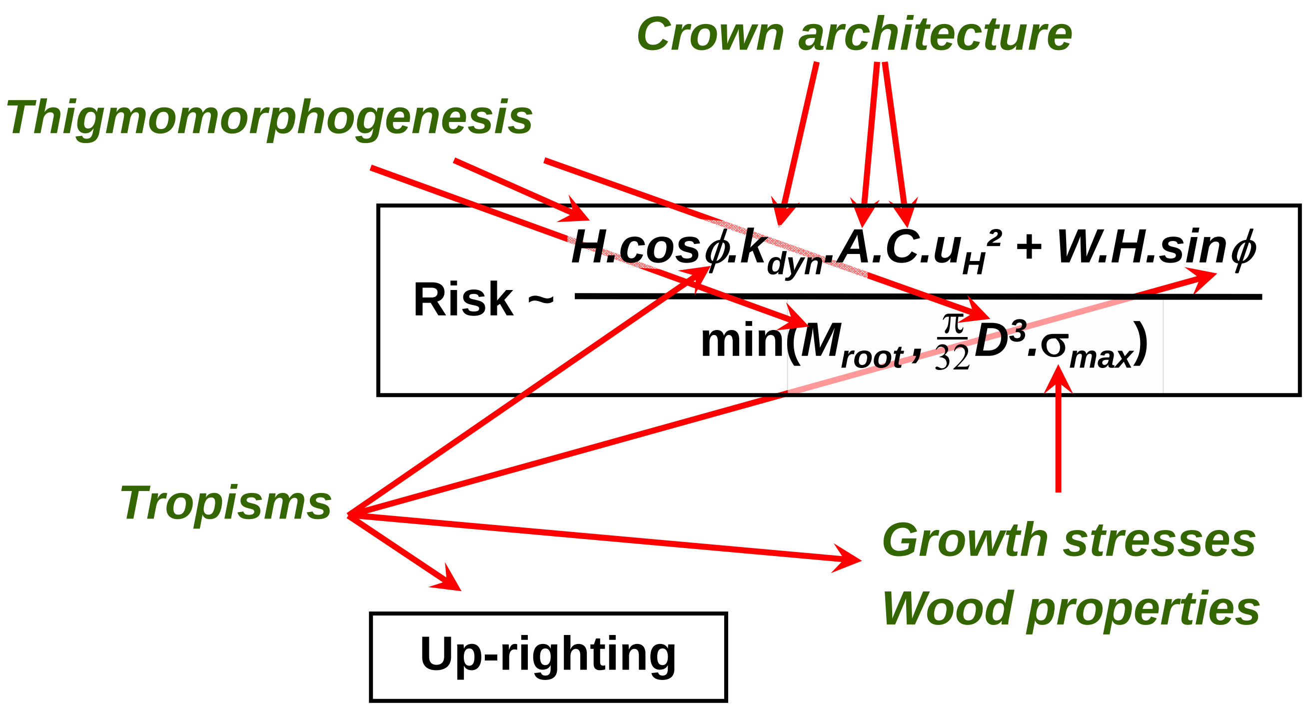
Reaction-juvenile-flexure wood
⇒ Variations in:

- Modulus of elasticity
- Compressive/tensile strength
- Growth stress level

Relation between stem properties and material properties is not always simple…

Tree biomechanics and tree stability

Summary: effects of adaptive growth



Tree biomechanics and tree stability

Challenge: modeling tree acclimation…
in the framework of PlantBioM (*an* agropolis fondation *project*)