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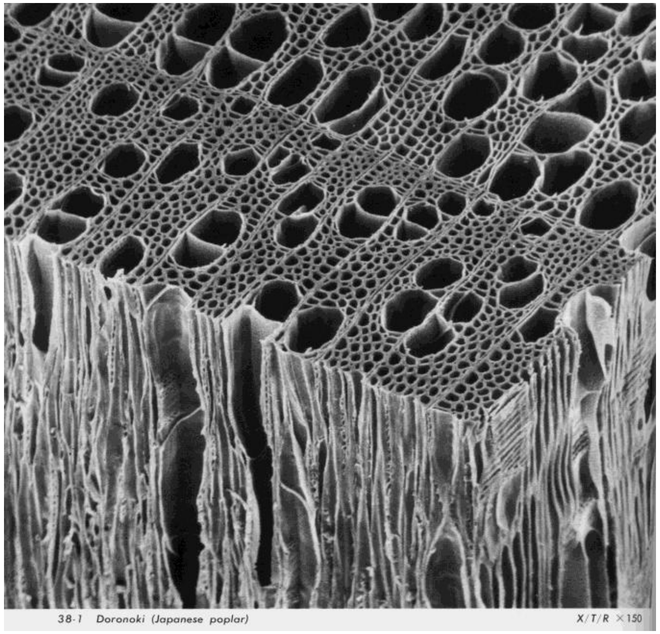

TREE BIOMECHANICS AND THE TRANSITION FROM JUVENILE TO MATURE WOOD

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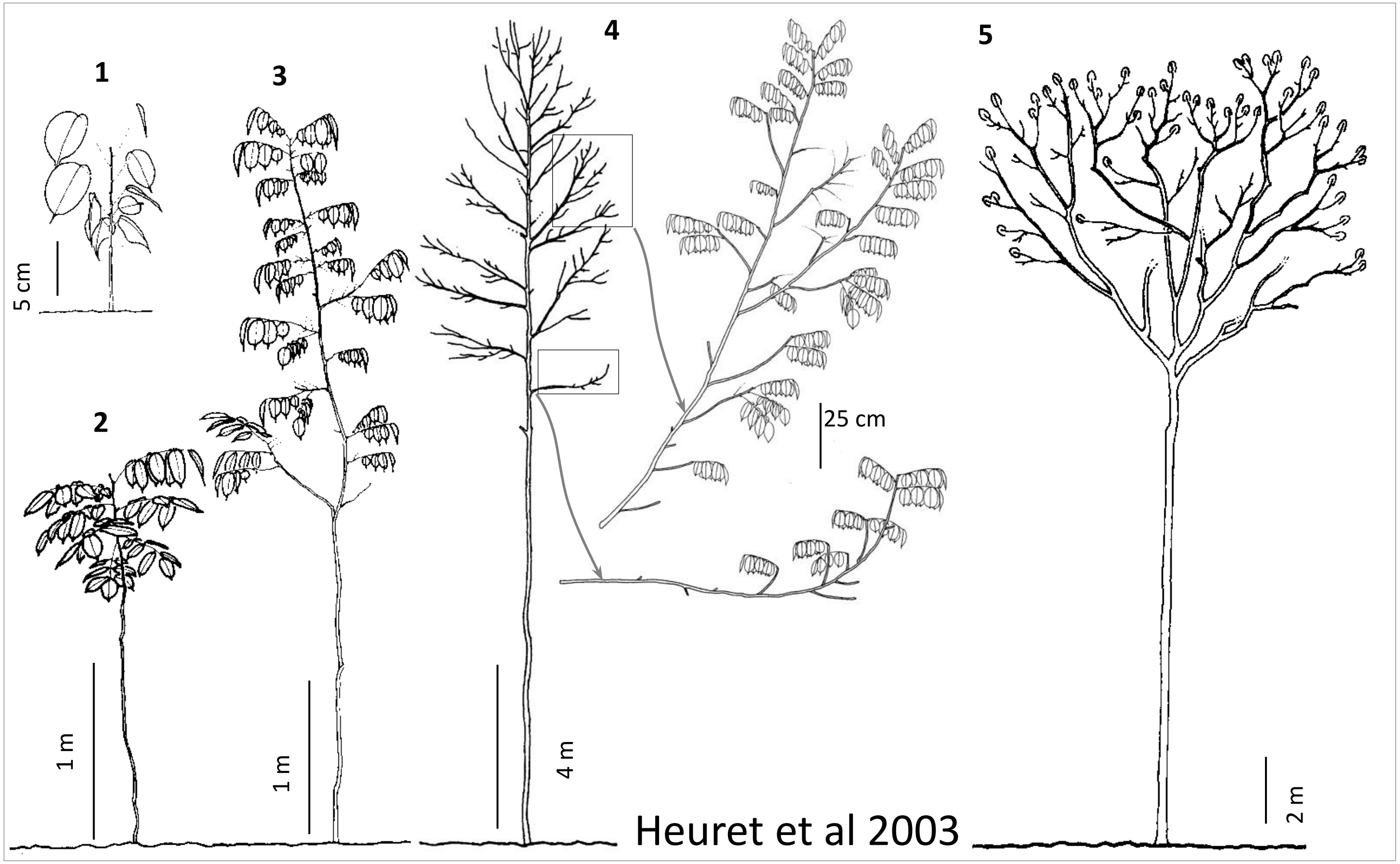
Wood Science for the Future

Juvenility in tree construction

- Juvenility regards the beginning of tree construction, when the tree is still young
  - Architectural juvenility for tree geometry
  - Xylem juvenility for wood as building material
- Two kind of juvenile behaviour are possible:
  - Ontogenetic juvenility depending only on the ageing of buds and cambium
  - Environmental juvenility depending on the evolution of external constraints on tree growth during the first ages
- Main aspects for structural tree biomechanics:
  - Flexure and buckling due to wind and self weight
  - Geometry of the structure and building material
- Growth and xylem maturation
  - Xylem growth = cell division + cell expansion (until the end of primary wall making). *Xylem growth contributes to tree geometry*
  - Xylem maturation = fibre cell wall thickening (until the end of secondary wall making). *Xylem maturation contributes to properties of the building material*

Geometry of the tree structure

(result of xylem growth: cell division + cell expansion)



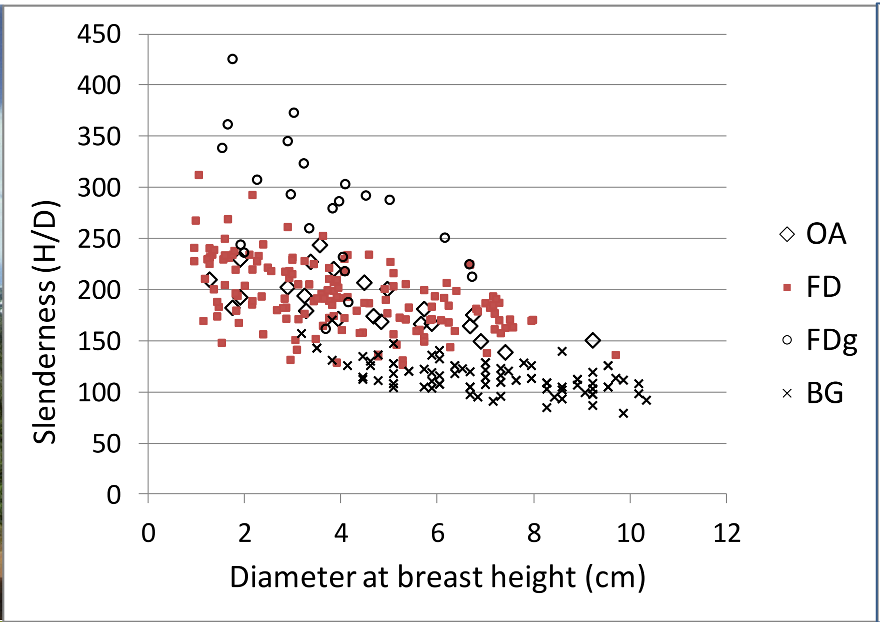
Heuret et al 2003

2 – 3 – 4: Setting of the architectural model during juvenile phase

Geometrical parameters: - Height (H), Diameter at breast height (D_{BH})

- Slenderness: H/D_{BH}, taper, form factor
- Crown height and diameter

Slenderness (H/D_{BH}), adaption to growing context

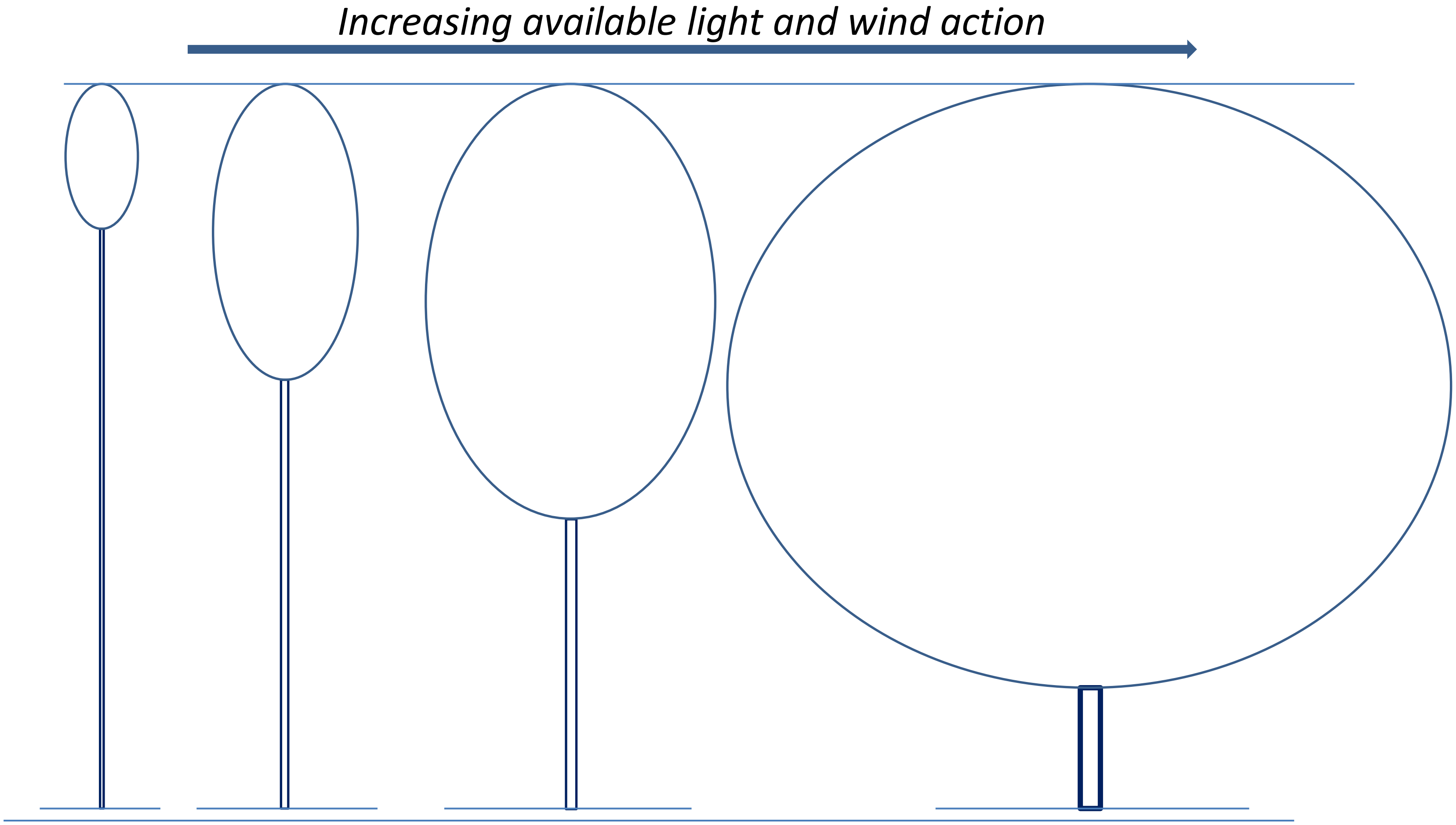


Juvenile growth in tropical forest

OA: dominated species
(Oxandra a.)
FD: 6 dominant species
FDg: Tachigali & Goupia
BG: Bagassa g. in
plantation

Huge variations in observed slenderness

associated with wind surface area (A_w) changes



Increasing available light and wind action

Gambler
H/D=200
A_w=1

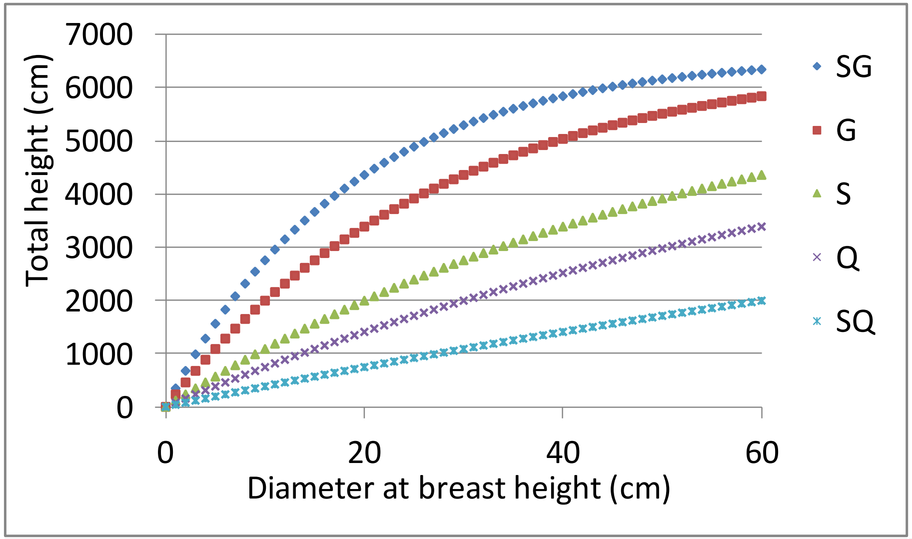
Slender
H/D=100
A_w=3,5

Quiet
H/D=70
A_w=9,5

Forest trees

Super quiet
H/D=36
A_w=27
Prairie tree

A simple model for trunk cylindrical growth



Model H(D)=a*(1-exp(-b*D)

a=6600 (asymptotic height in cm)

Super gambler: b=0,054; H(6,7cm)=20m

Gambler: b=0,036; H(10cm)=20m

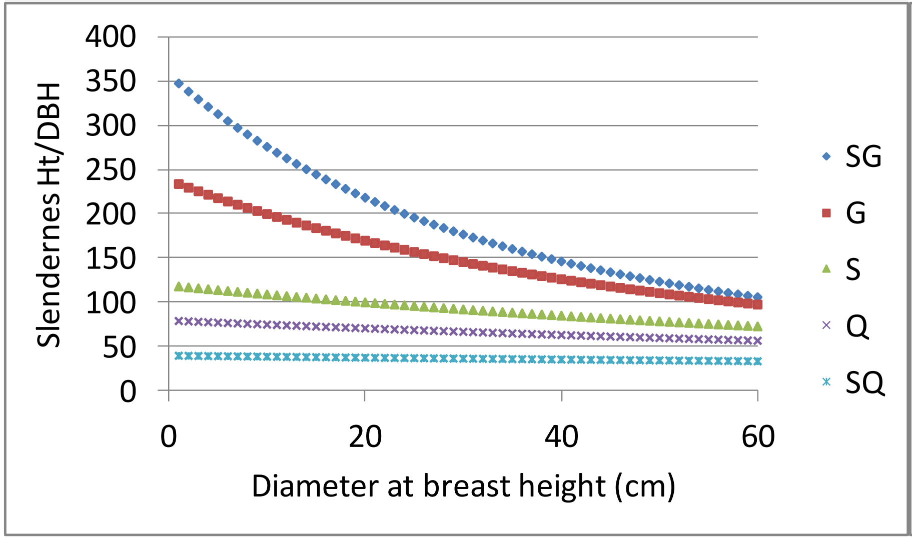
Slender: b=0,018; H(20cm)=20m

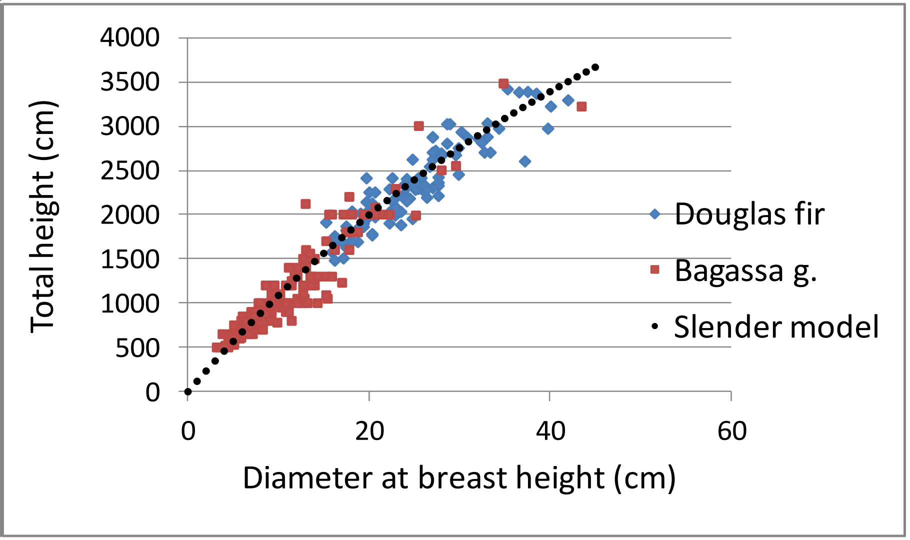
Quiet: b=0,012; H(30cm)=20m

Super: quiet b=0,006; H(60cm)=20m

Data for Douglas Fir: N. Décourt 1967

Data for Bagassa: ONF Guyane 2016

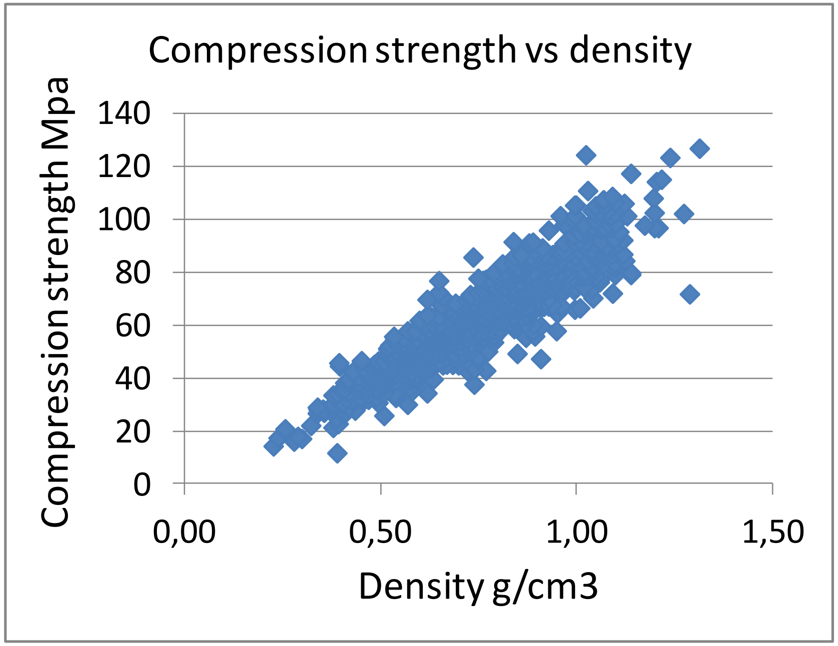




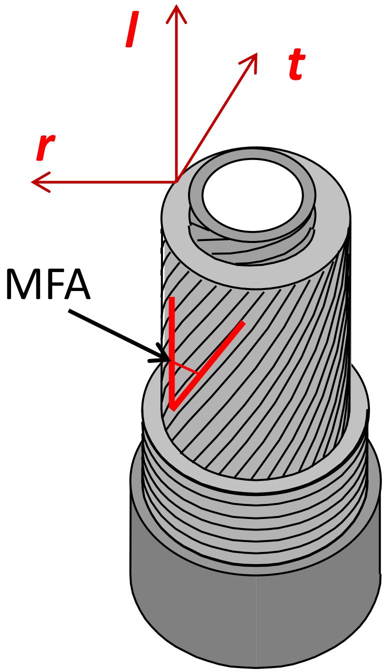
2 parameters: *a (Maximum height) and H(0)/D(0) (slenderness value at origin = a*b)*

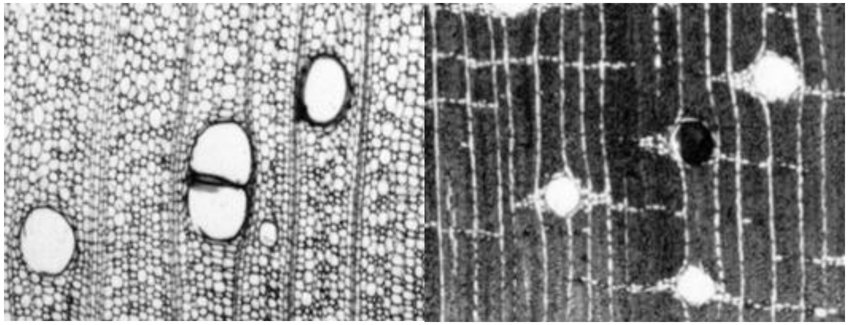
Properties of tree building material

(result of xylem maturation: fibre cell wall thickening)



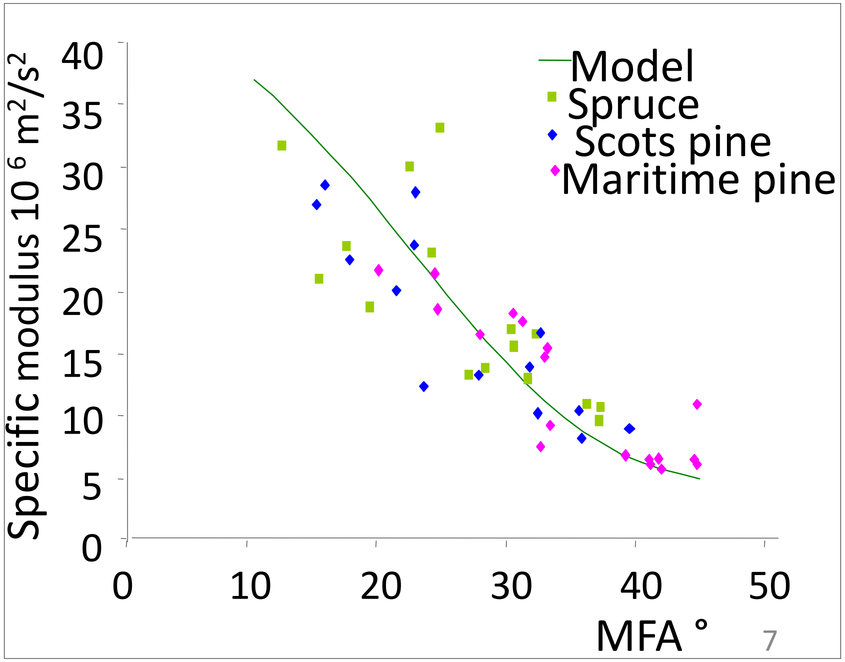
Specific modulus proxy of cell wall property in axial direction (linked to MFA and matrix chemistry)



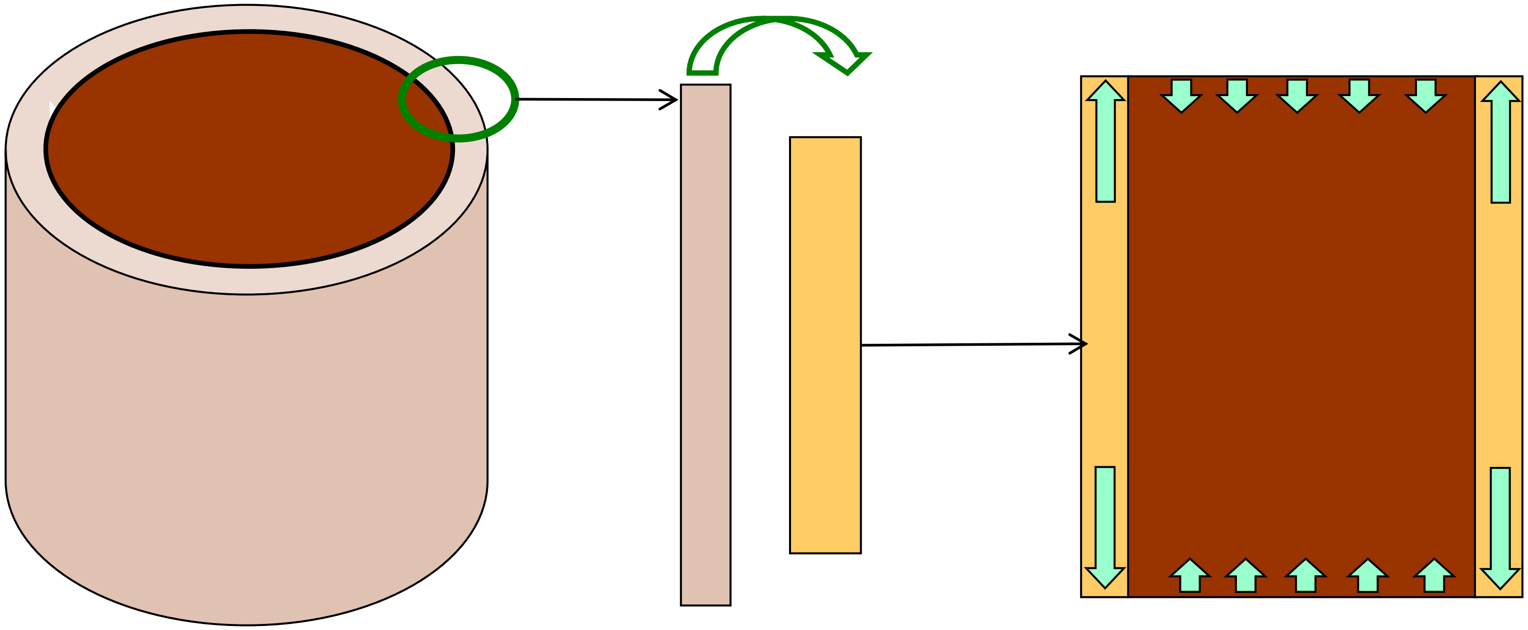


Balsa: Density = 0,15 *Swartzia: Density = 1,2*

Density proxy of the ratio: wall thickness/cell diameter



Growth stresses & fibre maturation process



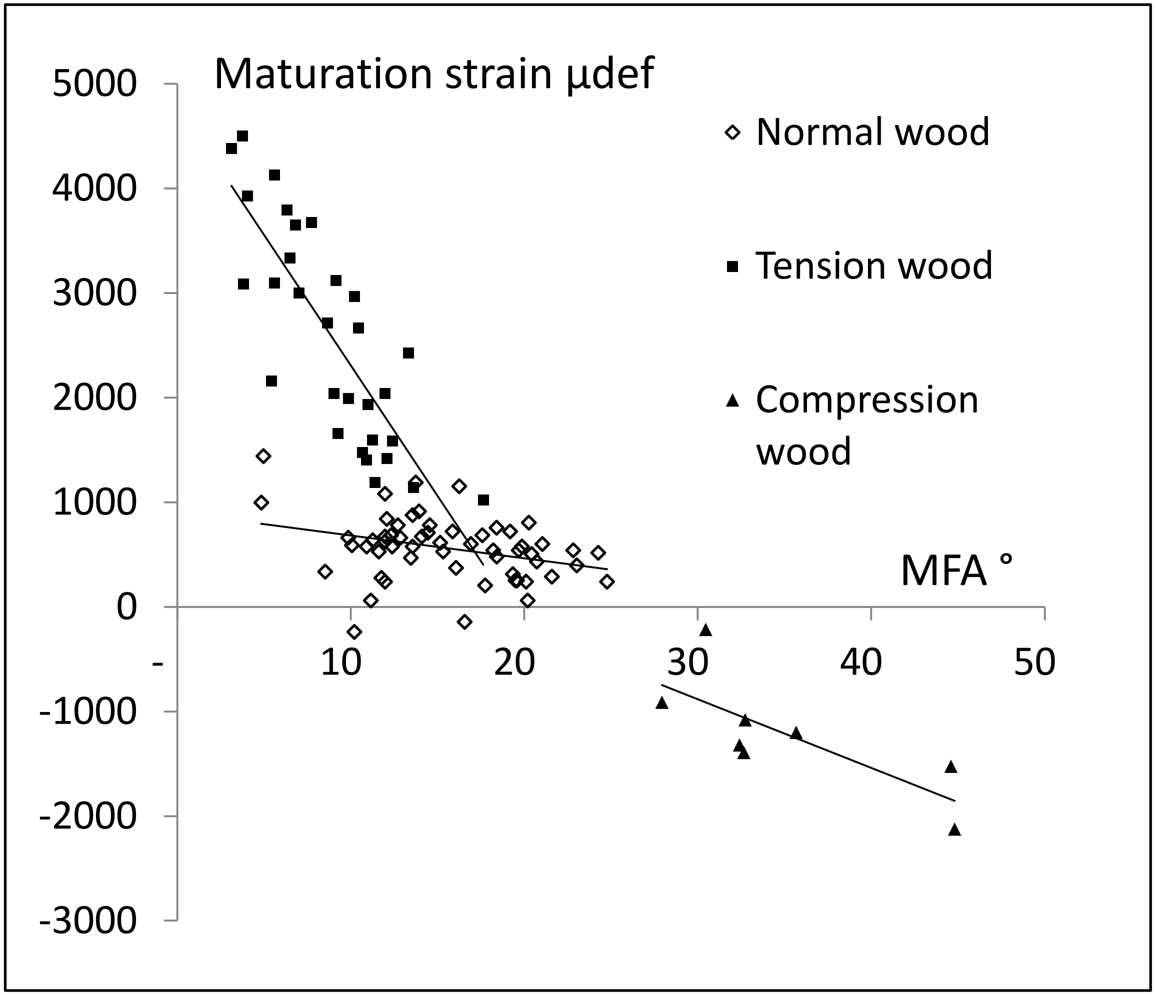
Step 1 Cell division creates a very soft new xylem layer

Step 2 Maturation of fibres induces layer shrinkage (*maturation strain*) in L direction while it stiffens

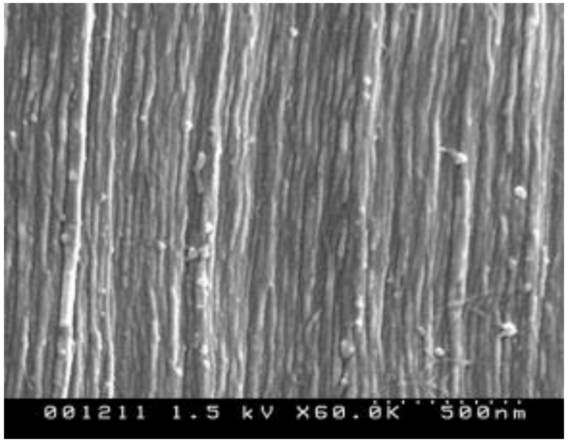
Step 3 Tensile forces created in the new layer are equilibrated by compression in the core xylem

Tensile stress in the new xylem layer depends on maturation strain, density and specific modulus

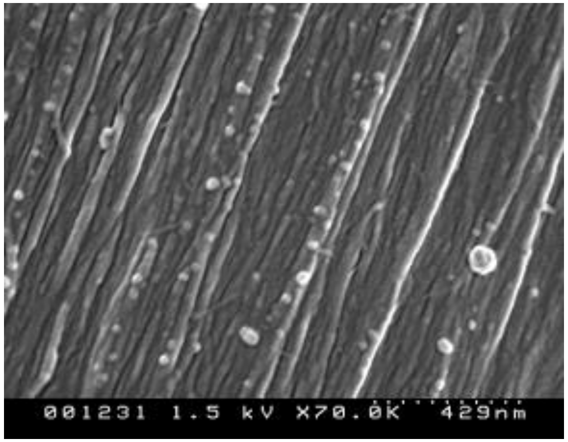
Maturation strain is depending on MFA and chemistry (strongly different in reaction wood)



Data from 3 angiosperms and 3 gymnosperms



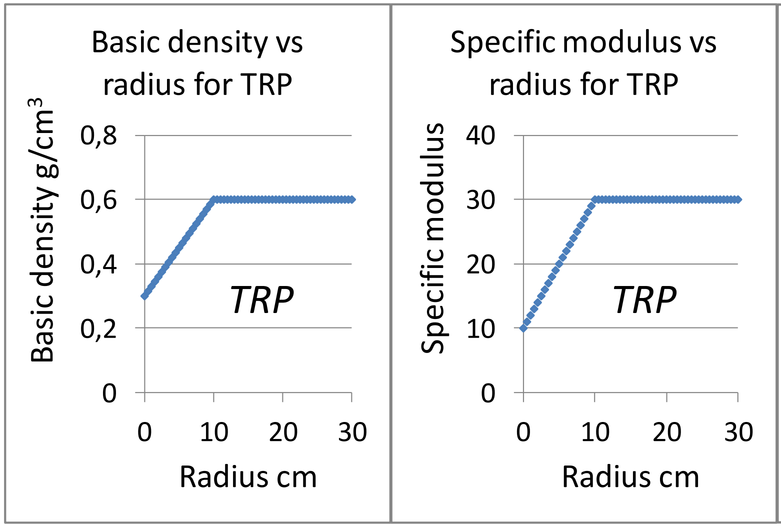
MFA = 4°



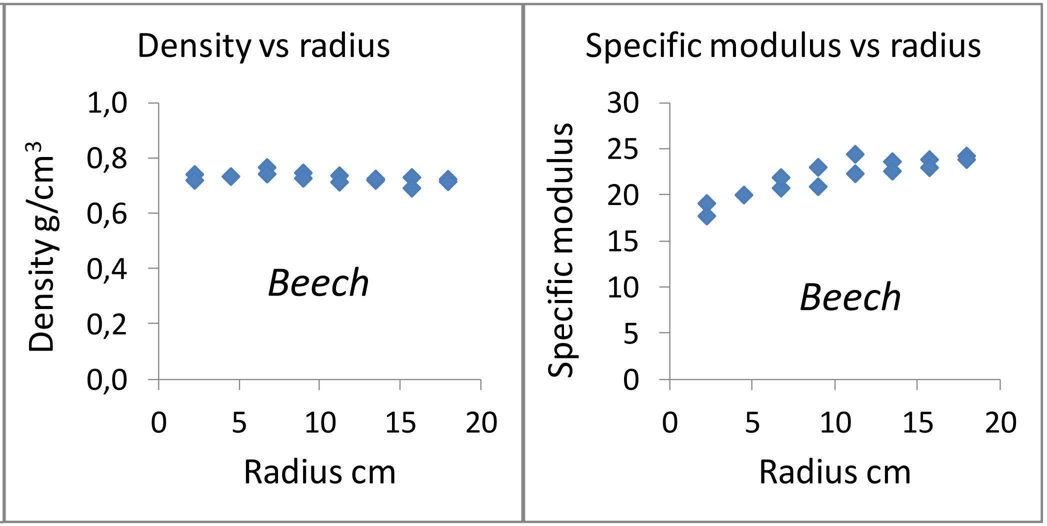
MFA = 24°

Simarouba

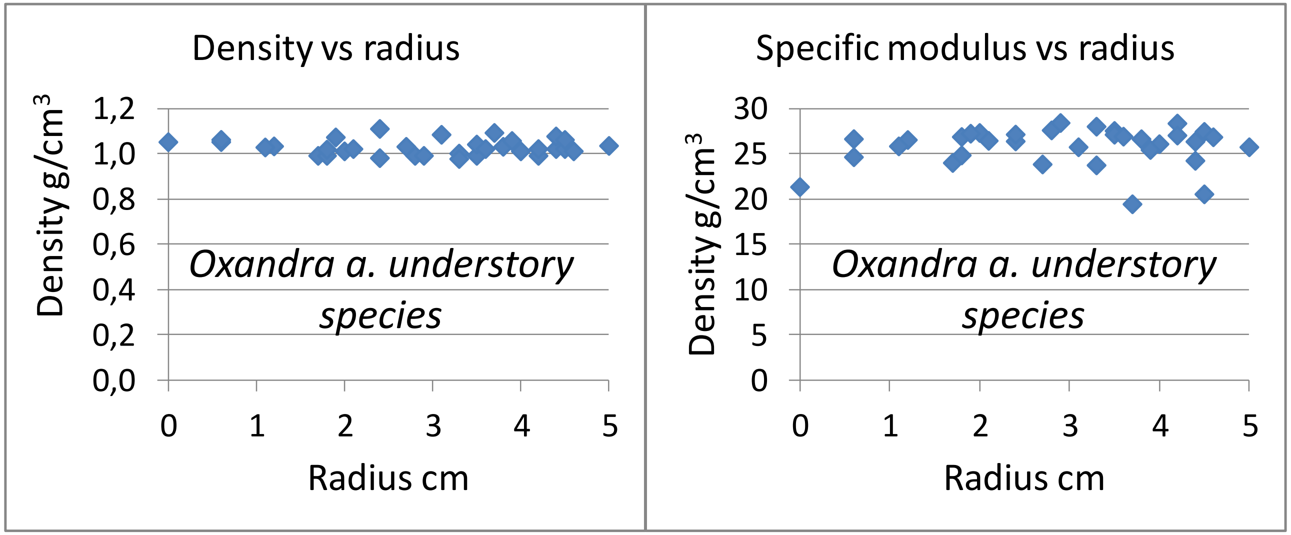
Juvenility in xylem properties



Typical radial pattern (Lachenbruch 2011)



Typical pattern for European Beech (Slender type)



Typical pattern for an understory species in French Guyana (Gambler type)

Simple models for xylem properties

(excluding reaction wood)

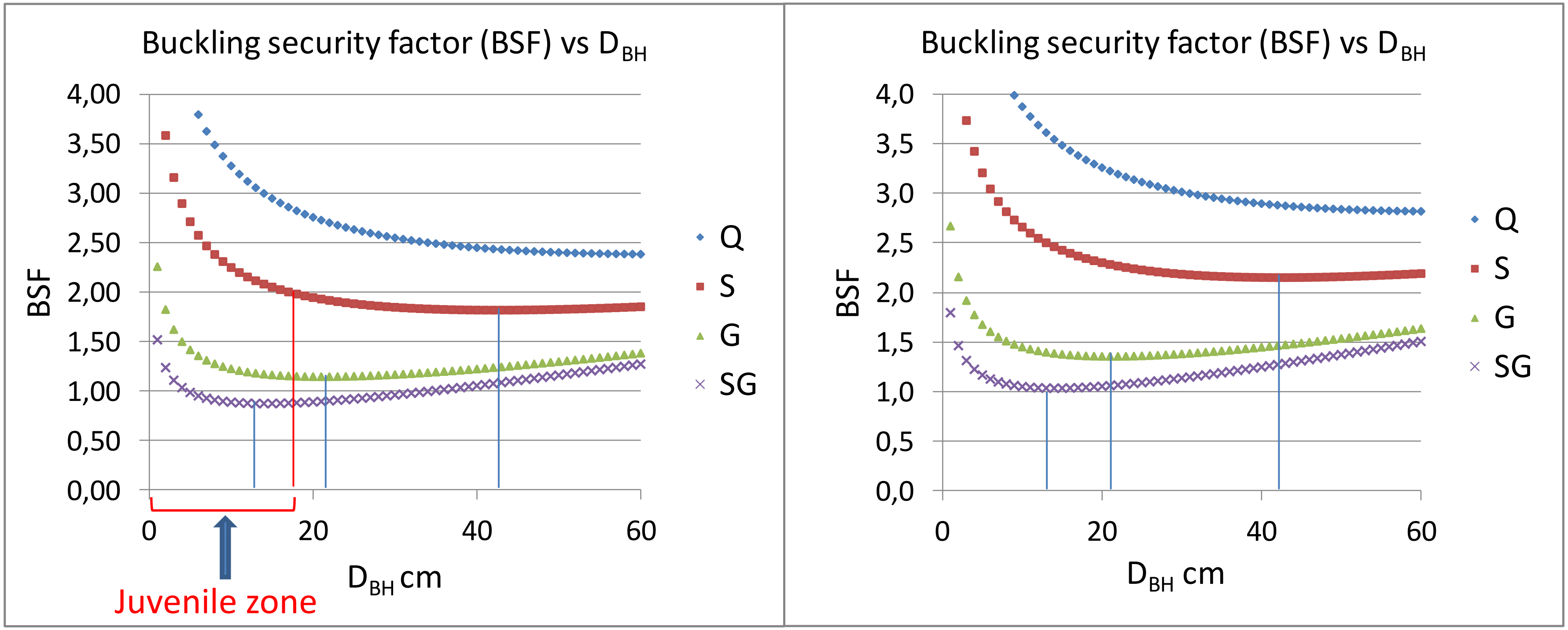
from different data bases: CTFT (Sallenave), Wood handbook (Kretschmann), Bridge project (Beauchêne), Reaction wood project (Gril) and papers on growth stresses (Yamamoto and others)

- Compressive strength proportional to basic density
- Green density proportional to the power 0,52 of basic density
- MOE proportional to both basic density and specific modulus
- Maturation strain: linear variation with specific modulus
- Maximum flexure strain in flexion: linear variation with specific modulus
- Pre-stressing at trunk periphery proportional to maturation strain, basic density and specific modulus

Basic growth simulation

- 5 different types of geometrical growth (H/D_{BH} varying from 33 to 330 for H=20m)
- Constant xylem properties (basic density and specific modulus)
- 3 different values of basic density from 300 to 900 Kg/m^3
- 3 different values of specific modulus from 15 to 30 $10^6*m^2/s^2$
- Radial increment of 5mm
- Inclusion of tensile pre-stressing in the compressive strength limit
- Buckling safety factor using Greenhill theory
- Calculus of:
  - Dry biomass (DBM)
  - Maximum flexure resistance (RCM)
  - Ratio of resistance on biomass (RCM/DBM)
  - Buckling safety factor (BSF)

Evolution of buckling security factor with diameter



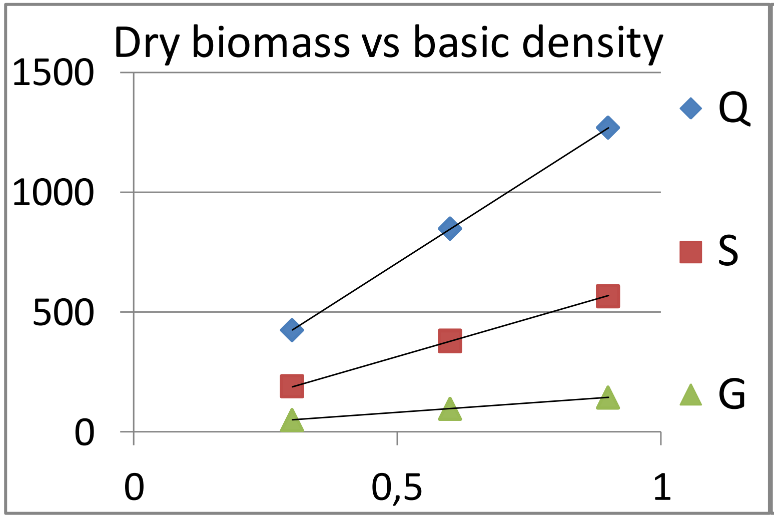
Standard wood
Basic density = 600 Kg/m^3
Specific modulus = 22*10^6 m^2/s^2

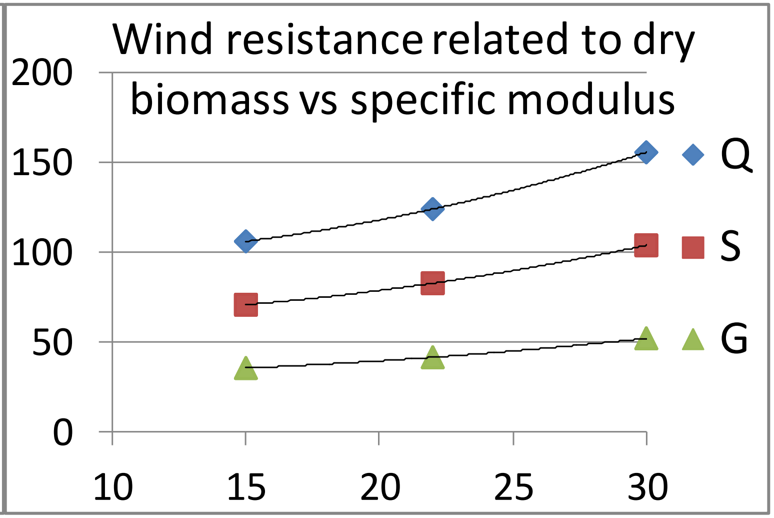
Strong wood
Basic density = 900 Kg/m^3
Specific modulus = 30*10^6 m^2/s^2

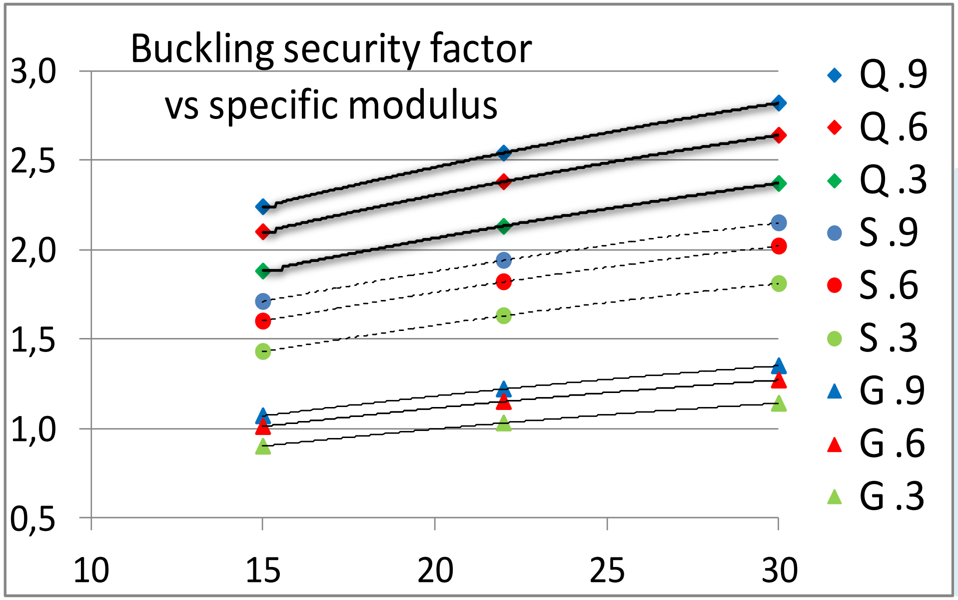
Q: quiet; S: Slender; G: Gambler; SG: Super gambler

There is a critical diameter at minimum buckling security factor (Sterk & Bongers 1998)
This diameter is lower for very slender trees and BSF is higher for strong wood (high MOE)
For slender trees there is a rather large zone in juvenile phase with a security factor above 2

Main results from simulation on structural behaviour







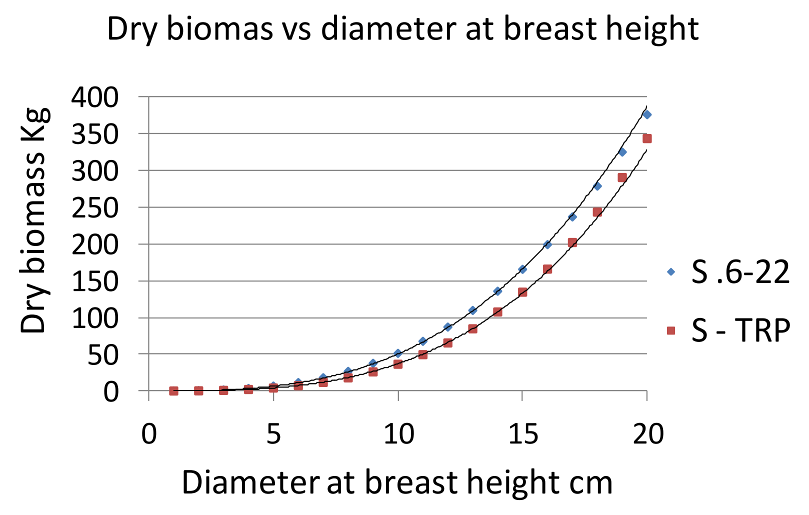
Q: quiet; .9, .6, .3: basic density
S: slender; .9, .6, .3: basic density
G: gambler; .9, .6, .3: basic density

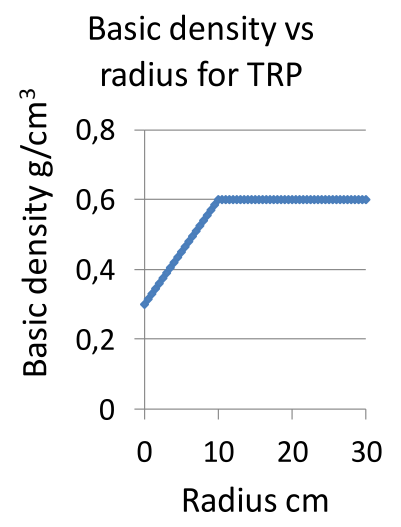
Slenderness (Q to G type) is by far the most influencing factor (reg. coeff. > 90%)

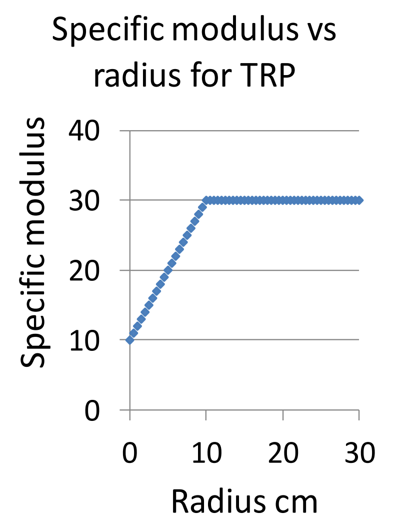
Within a type:

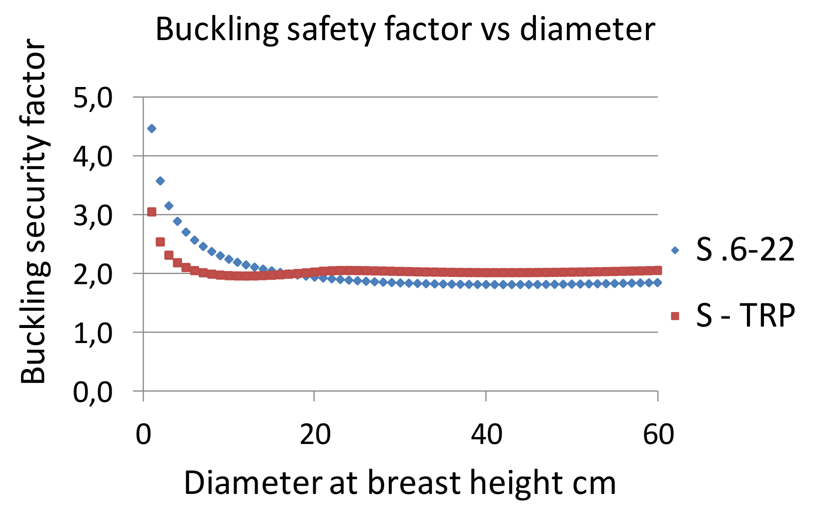
- *Dry biomass depends only on basic density*
- *Resistance to wind relative to dry biomass depends only on specific modulus*
- *Buckling security factor depends mainly on specific modulus but also on basic density*

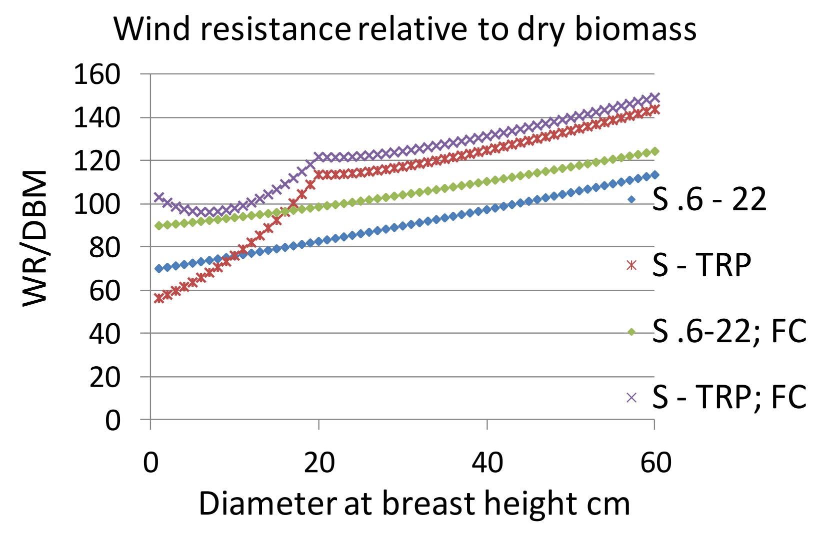
Impact of typical radial pattern (TRP)


Dry biomas vs diameter at breast height


Basic density vs radius for TRP


Specific modulus vs radius for TRP

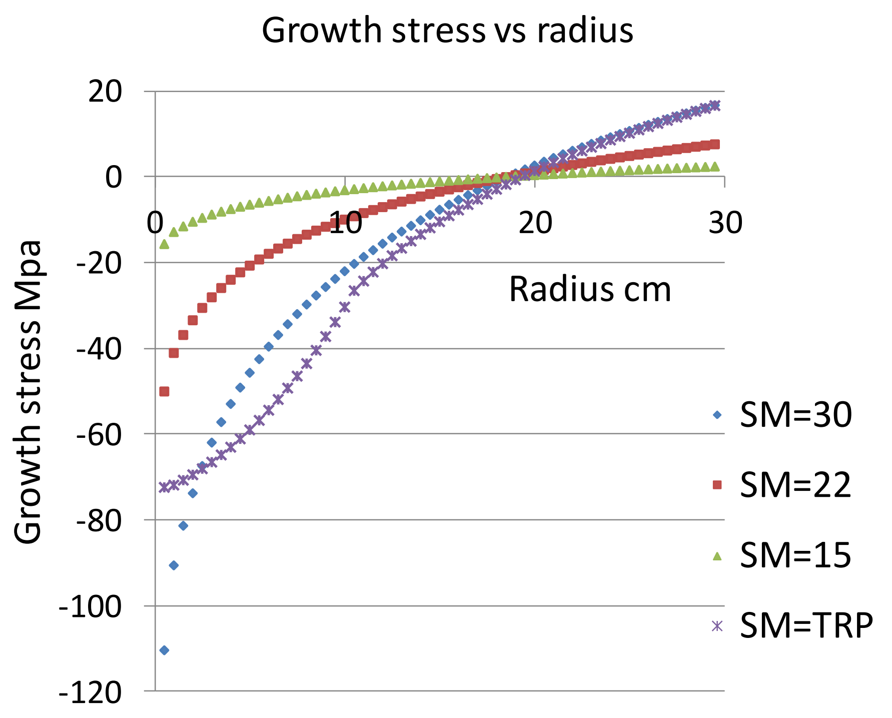

Buckling safety factor vs diameter

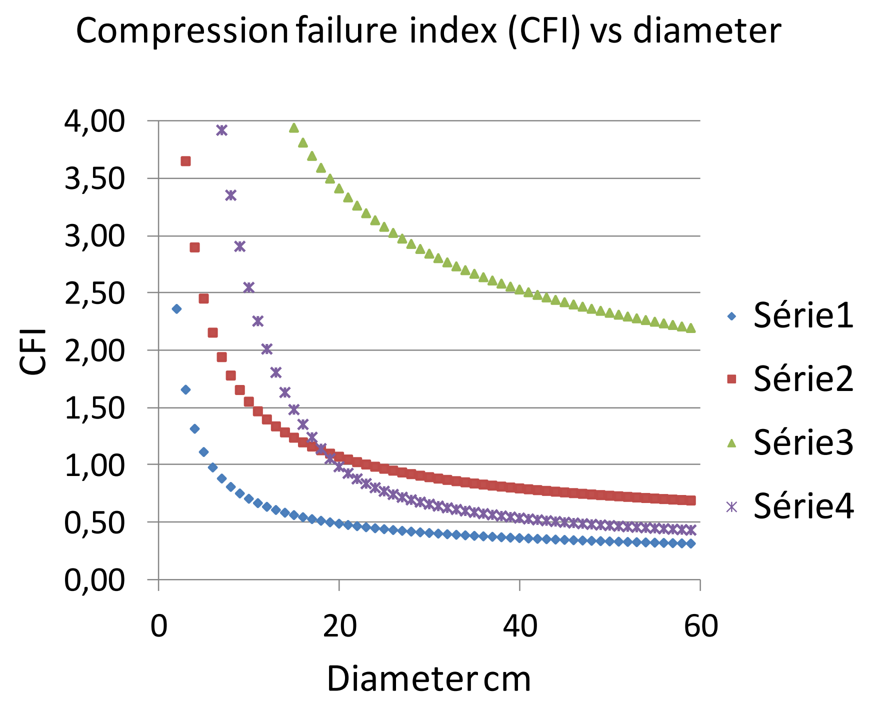

Wind resistance relative to dry biomass

FC: correction using tree flexibility (maximum elastic deflexion before damage

Buckling safety factor keeps close to 2 in the juvenile phase, with an improvement in other responses

Growth stress results and impact of TRP


Growth stress vs radius


Compression failure index (CFI) vs diameter

Compression failure index: ratio between growth stress and compressive strength at the centre.

- Growth stress level depends both on radius, basic density and specific modulus.

- The risk of compression failure grows both with diameter and specific modulus.

- TRP lowers the risk of compression failure

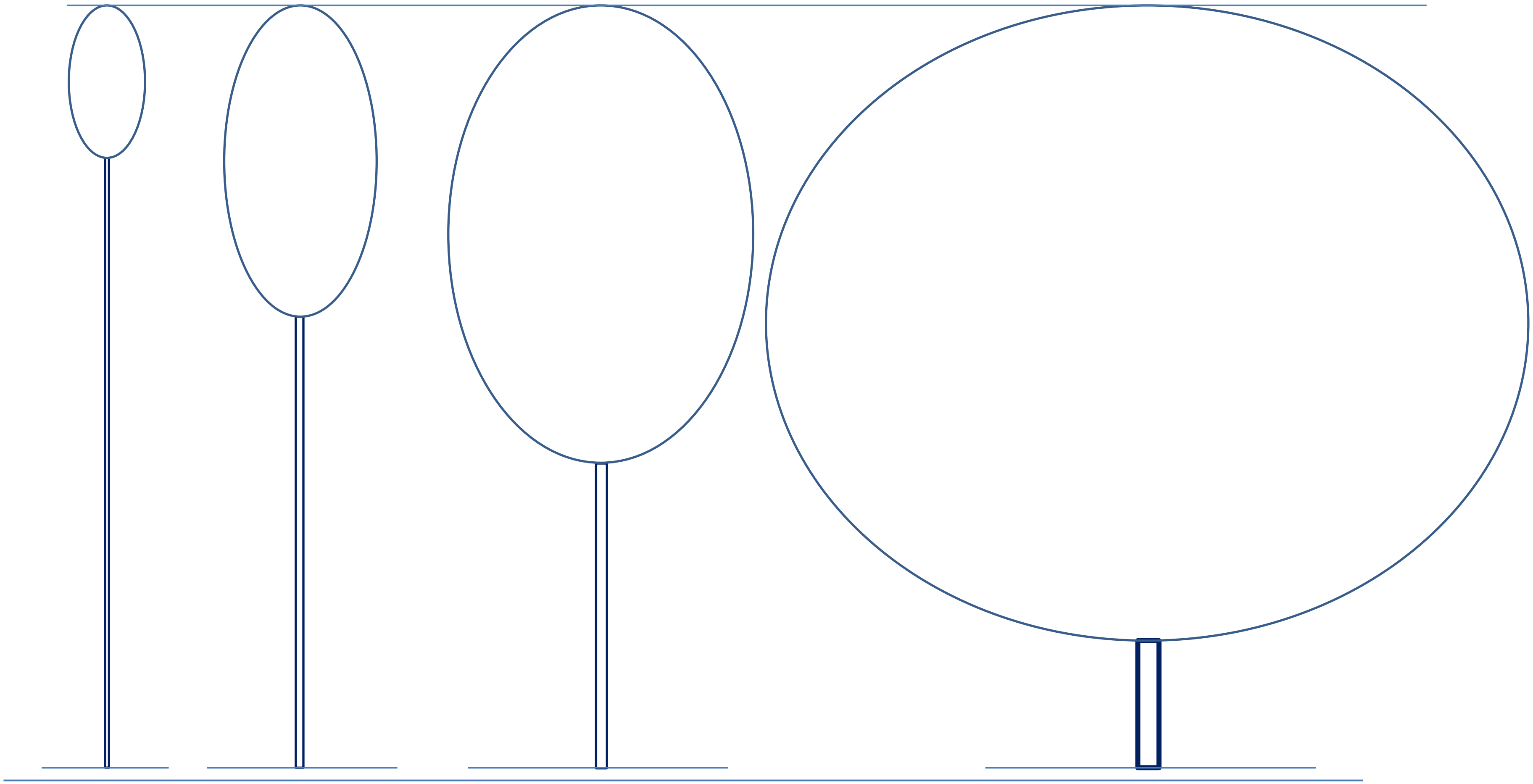
Conclusion

- Mechanical juvenility seems to be mainly adaptive
- The most important parameters in mechanical adaption are geometrical
- Slenderness (total height/diameter at breast height) of the young tree is a good indicator for adaption, its range is high, from 30 to 300
- Physical and mechanical properties are second order parameters
- Basic density combined to slenderness is the key for dry biomass at a given tree height
- Specific modulus (square of sound speed in dry wood) combined to slenderness is the key for wind resistance relative to dry biomass
- Both specific modulus and basic density combined to slenderness are keys for buckling security
- There is a critical diameter (minimum BSF), rather low for very slender trees which needs rather high values of basic density and specific modulus (Sterk & Bongers 1998)
- For usual slender forest trees, buckling risk is low in the juvenile phase
- Gradients in basic density and specific modulus in the juvenile phase:
  - *keeps buckling risk at reasonable value*
  - *lowers dry biomass,*
  - *Improves the resistance to wind relative to dry biomass*
  - *Lowers growth stresses at heart and thus the risk of compression failure in trunk centre*

Thanks for your attention

Aknowlegments

- Many results used to build the model come from recent Master (P. Tabarant) and PhD works (G. Jaouen, R. Lehnebach, J. Bossu) in EcoFoG laboratory (French Guyana) under the supervision of T. Alméras, J. Beauchêne, B. Clair, M. Fournier, P. Heuret or E. Nicolini.
- Many also come from long term systematic measurements of wood properties in Nancy (LERFOB) and Montpellier (CIRAD) associated to numerous projects concerning wood quality of often less known species and growth stresses in trees, thanks to J. Gérard, JM. Leban, F. Mothe or A. Thibaut
- Most of the ideas, theories and calculations come from the work of M. Fournier, J. Dlouha, G. Jaouen & T. Alméras (Journal of experimental botany 2013).
- I was inspired both by these recent works and by discussions with B. Gardiner, B. Lachenbruch and F. Telewski to try this general but simplistic approach.



H/D=200	H/D=100	H/D=70	H/D=36
H=0,2*H	H=0,4*H	H=0,6*H	H=0,85*H
L=0,1*H	L=0,2*H	L=0,4*H	L=1,0*H
S=0,02pi*H2	S=0,08pi*H2	S=0,24pi*H2	S=0,85pi*H2
1	4	12	42,5
Hv=0,9*h	Hv=0,8*h	Hv=0,7*h	Hv=0,575*h
Mv=0,018*H3	Mv=0,064*H3	Mv=0,172*H3	Mv= 0,489 *H3
1	3,55	9,55	27,15