Thigmo What? Thigmomorphogenesis! How trees respond to wind..

California Tree Failure Program
Filoli Center
Woodside, California
January 8, 2015

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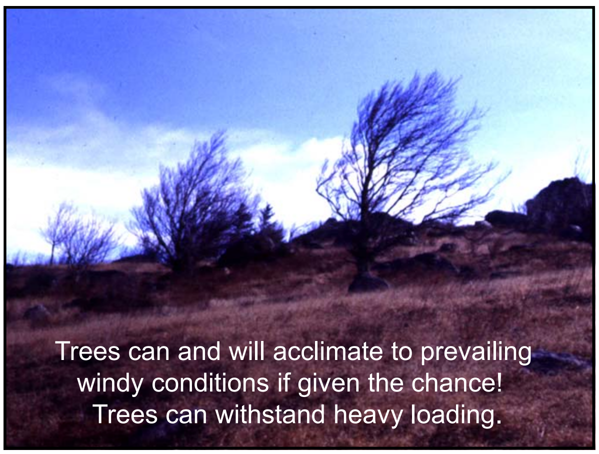
Outline

- Brief historical overview of the past 205 years of thigmomorphogenetic research
- Thigmomorphogenesis in Trees-
  - Wind drag and streamlining
  - Physiology and developmental anatomy
  - Biomechanics
- Applications in the urban forest



How do trees respond to wind and other mechanical stresses?

Trees can alter their canopy structure, growth rate, anatomy, morphology, and mechanical strength of their wood in response to wind.

Influence of mechanical stimuli on plants recognized at least since Theophrastus (300 B.C.E.)

Trees growing in windy environments were shorter in height, shorter internodes (more knots), less straight, closer grain, and harder wood.

"*The region, in a word, must have good winds, this being not the same as to have no winds, and a windy region is definitely stunting to growth*" (p215)

"*…in windless and shaded places the trees always grow up erect and undistorted, with fewer knots and taller; whereas in well-ventilated, windward and sunny places, apart furthermore when among trees growing far apart, they do not do this to the same extent, since not only does lateral growth prevent height, but also the wind makes the trees rough, producing knots, because the winds check the movement of the food.*" (pp 261-263)

Theophrastus 371-287 B.C. E.

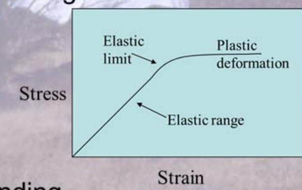
Knight 1803

First experiment with staked and free swaying apple trees (flexing: alternating tension and compression)

"If a tree be placed in a high and exposed situation, where it is much kept in motion by winds, the new matter which it generates will be deposited chiefly in the roots and lower parts of the trunk; and the diameter of the latter will diminish rapidly in its ascent. . . . the growth of the insulated tree on the mountain will be, as we always find it, low and sturdy, and well calculated to resist the heavy gales to which its situation constantly exposes it" p. 281

Stress and Strain relations in plants: Lessons from the world of mechanics

- Stress- applied force
- Strain- resultant deformation or change in the object or material being stressed (response)
- Tolerate the stress
- Avoid the stress
- Elastic deform.
- Plastic deform- Wounding

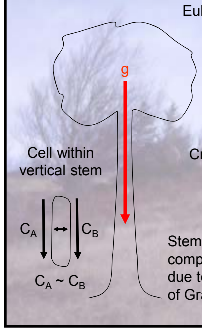


"We may say that the plant has the ability to respond to stress, but the notion *stress* is complex and will doubtless by future research be subdivided." **Newcombe 1895**

Pure Tension:	**Pure Compression:**	**Sway:**	**Bending or displacement:**
pulling apart	**pushing together**	**alternating compression and tension**	**Static compression and tension**
Rare except in vines and tendrils	*Self-loading- gravity on stem mass*	*Common due to wind induced sway*	*Common due to a number of environmental factors*

Mechanical Forces on Trees

Self-Loading: perceiving one's own weight Acceleration due to gravity



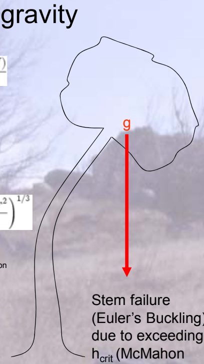
Euler's Buckling- $F = \frac{(K\pi^2 EI)}{l^2}$

F = maximum or critical force (vertical load on column)
E = modulus of elasticity
I = area moment of inertia
l = unsupported length of column
K = a constant for one end fixed and the other end free to move laterally *K* = 1/4;

Critical Height- $h_{crit} = \left(\frac{2.5Er^2}{\rho g}\right)^{1/3}$

ρ = density
E = Young's modulus
r = radius vertical column of circular cross section

Stem under compression load due to acceleration of Gravity

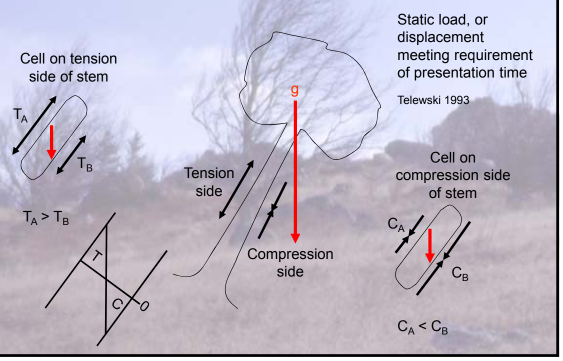


Stem failure (Euler's Buckling) due to exceeding h_{crit} (McMahon 1973)

Euler's Buckling-

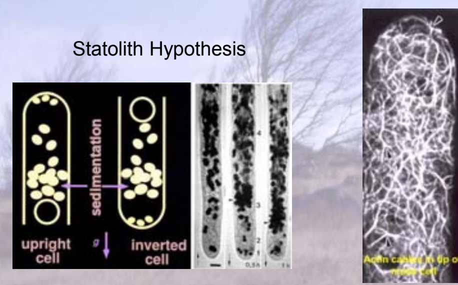
In *Larix* at Strbske Pleso after blowdown or windthrow event.

Gravity: sensing of differential loading on plasmamembrane?



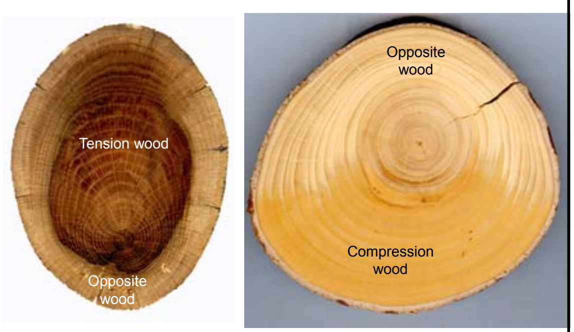
Gravitropism: perceiving and reorientation with respect to the gravitational field

Statolith Hypothesis



Amyloplasts, starch grains, statoliths

Dr. Fred Sack, Ohio State University: www.biosci.ohio-state.edu/pcmb/osu_pcmb/people/fred_sack/sack_research_moss_grav_research.htm

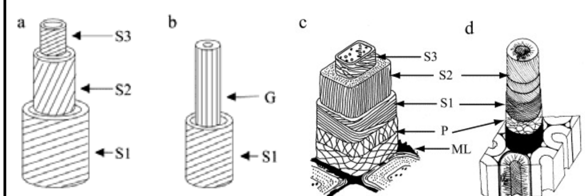


White Oak (*Quercus alba*)

Eastern White Pine (*Pinus strobus*)

What's in a cell wall? Generation of growth strains

- Normal wood and Tension wood gelatinous fiber
- Normal wood and Compression wood tracheid

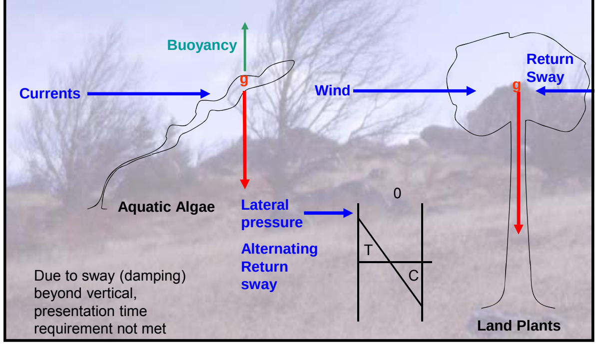


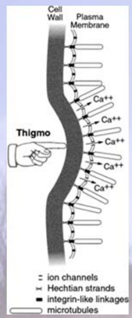
Kwon et al. 2001. Phytochemistry 57:847-857

Pressure Waves: Thigmorphogenesis

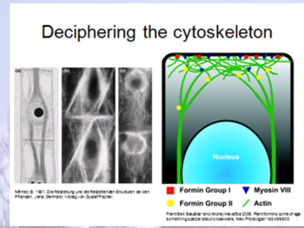
- Wind
- Water currents and tides
- Mechanical contact
  - Fungal penetration peg
  - Animals brushing past vegetation
  - Roots or stems pushing through soil

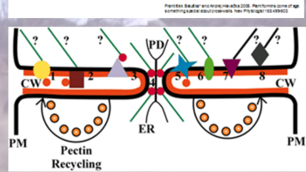
Pressure Waves: Thigmorphogenesis





M. J. Jaffe, A. C. Leopold, and R. C. Staples 2002. Thigmo responses in plants and fungi Am. J. Botany 89: 375-382





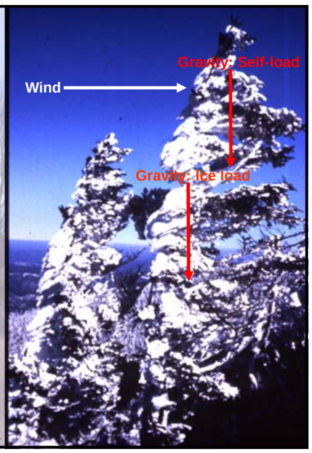
F. Baluska, J.f Samaj, P. Wojtaszek, D. Volkmann and D. Menzel 2003. Cytoskeleton-Plasma Membrane-Cell Wall Continuum in Plants. Emerging Links Revisited. Plant Physiology 133:482-491

Thigmomorphogenesis in Trees-

- Wind drag and streamlining
- Physiology and developmental anatomy
- Biomechanics

Mechanical Loads acting on a tree during winter

Evidence for a 'long-term' memory of loading during winter months (Valinger *et al.* 1994)



Telewski, F.W. 1982, Roan Mtn., N.C., U.S.A.

What is Streamlining?

- The ability of a tree to alter its canopy shape, either by breakage and loss of branches or by sweeping back of branches in response to a prevailing wind, thereby reducing drag upon the tree.

Wind Effects in Trees

Not all species streamline alike!

- Streamliners (wind avoiders):
  - Eastern white Pine
  - Douglas fir
  - Ponderosa pine
  - True firs
  - Willow
- Non-streamliners (wind tolerators):
  - Austrian pine
  - Honey locust

TABLE 2. Species comparison to greenwood biomechanical properties. Species are listed from most sensitive to least sensitive to crown deformation due to wind. Wood property data from Kretschmann [58]

Species	Specific Gravity[a]	Modulus of rupture (kPa)	Modulus of elasticity (MPa)	Work to maximum load (kJ/m³)	Impact bending (mm)	Compression perpendicular to grain (kPa)	Shear parallel to grain (kPa)
Western Larch (Larix occidentalis)[c]	0.55-0.48	60,000-53,000	11,400-10,100	71	740	30,500-25,900	6,300-6,000
Tamarack (Larix laricina)[c]	0.48	47,000	8,600	-	-	21,600	6,300
Coastal Douglas fir (Pseudotsugamenziesii)	0.45	53,000	10,800	52	660	26,100	6,200
Ponderosa pine (Pinus ponderosa)	0.38	51,000	6,900	36	530	16,900	4,800
Balsam Fir (Abies balsamea)	0.34	36,000	7,800	32	410	16,800	4,700

[a]Specific gravity is based on weight when ovendry and volume when green

[b]Modulus of elasticity measured from a simply supported, center-loaded beam, on a span depth ratio of 14/1. To correct for shear deflection, the modulus can be increased by 10%.

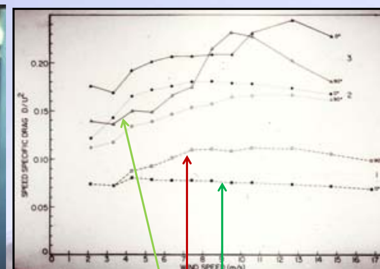
[c] Wade and Hewson [30] when discussing sensitivity to wind only reference *Larix* sp. but Owada [59] specifically studied *Larix leptolepis* (*L. kaempferi*). Unfortunately, greenwood data for this species was not presented in Kretschmann [58]

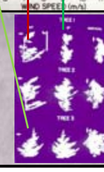
Telewski 2012

Different Frasier fir crowns exposed to different levels of wind on Roan Mtn., N.C.

Telewski & Jaffe 1986

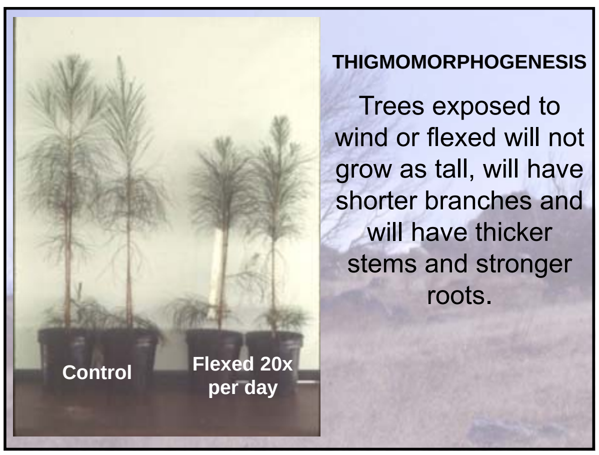
SO, why streamline?



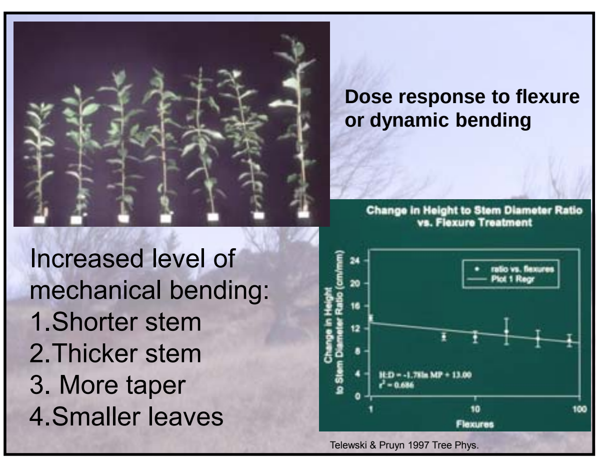


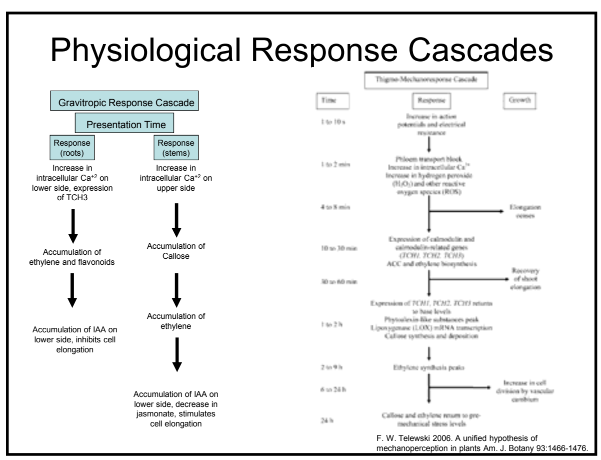
Streamlining of crowns reduce wind loading by reducing the speed specific drag. Avoidance of stress by shedding the load.

Telewski & Jaffe 1986


THIGMOMORPHOGENESIS
Trees exposed to wind or flexed will not grow as tall, will have shorter branches and will have thicker stems and stronger roots.
Control
Flexed 20x per day


Flexed 20x per day
Control
Trees exposed to flexing are more wind firm
Telewski Unpublished 1982

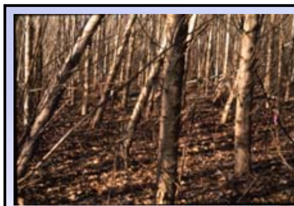

Dose response to flexure or dynamic bending
Increased level of mechanical bending:
1.Shorter stem
2.Thicker stem
3. More taper
4.Smaller leaves
Change in Height to Stem Diameter Ratio vs. Flexure Treatment
ratio vs. flexures
Plot 1 Regr
Change in Height to Stem Diameter Ratio (cm/mm)
Flexures
0
4
8
12
16
20
24
1
10
100
Telewski & Pruyn 1997 Tree Phys.


Physiological Response Cascades
Gravitropic Response Cascade
Presentation Time
Response (roots)
Response (stems)
Increase in intracellular Ca+2 on lower side, expression of TCH3
Increase in intracellular Ca+2 on upper side
Accumulation of ethylene and flavonoids
Accumulation of Callose
Accumulation of IAA on lower side, inhibits cell elongation
Accumulation of ethylene
Accumulation of IAA on lower side, decrease in jasmonate, stimulates cell elongation
F. W. Telewski 2006. A unified hypothesis of mechanoperception in plants Am. J. Botany 93:1466-1476.

Mechanical Properties of Wood

- Strong in tension
- Weak in compression

- How do wood properties change in response to dynamic flexing (thigmo.) vs. static displacement (gravitropism)?
- Can wind induce reaction wood formation?



Photos: Constance Harrington, USFS

The tale of two poplar clones:

One tolerant of wind, one susceptible to wind snap.

When exposed to wind, the wind tolerant clone grew more radially (higher I) and had more flexible wood (lower E) than the susceptible clone.

The wind tolerant clone was exhibited a greater thigmomorphogenetic response.

Pruyn, Ewers, & Telewski 2000

What is Flexural Stiffness?

Strength of Douglas fir Timbers

2 x 8 vs. 2 x 12

2 x 8 Floor Joist

h

b

E, Elastic modulus of Douglas fir = 13 x 10^9 N/m^2 (Gpa)

I, Second moment of cross sectional area = I = bh^3/12

EI = 46.17 x 10^4 N/m^2
Or
EI = 461,700 N/m^2
Or
EI = 67 psi

2 x 8 Scaffold Plank

h

b

EI = 2.89 x 10^4 N/m^2
EI = 4 psi

2 x 12 Floor Joist

h

b

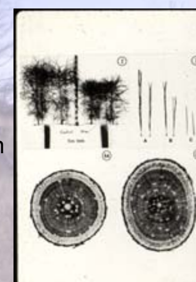
EI = 155.83 x 10^4 N/m^2
EI = 225 psi

Flexure Wood in Conifers

- Intermediate between ‘Normal’ and Compression wood.
  - Increase in MFA
  - Increase in Wood Density
  - Sorter tracheid length
  - Slight increase in lignification

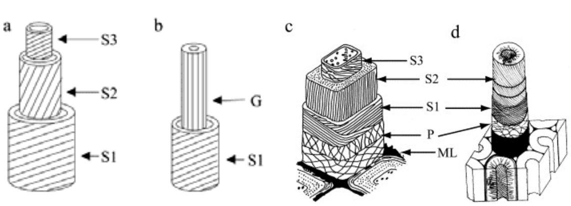
Telewski, F.W. 1989. Tree Physiology 5:113-121

Telewski, F.W. & Jaffe, M.J. 1981. Can. J. For. Res. 11:380-387



What’s in a cell wall?

- Normal wood and Tension wood gelatinous fiber
- Normal wood and Compression wood tracheid



Kwon et al. 2001. Phytochemistry 57:847-857

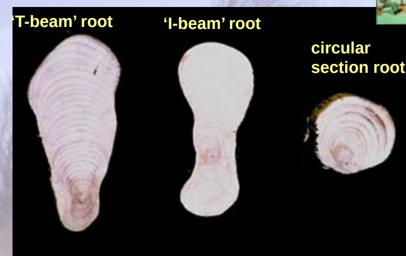
Flexure Wood in Porous Wood Angiosperms

- Will it be similar to Tension Wood? **NO**
  - Increase in MFA angle (decrease in TW)
  - No significant change, slight increase in lignin content (decrease in TW)
  - No significant change in Glucose (cellulose) maybe slight decrease (increase in TW)
  - A few Gelatinous Fibers but not more than in control trees, but thicker fiber walls (increase in TW)
  - Reduced Vessel area (similar to TW)
  - Increase in Syringyl content (no change in TW)

Roots will respond to wind.

Photos: F.W. Telewski

Root cross-sectional shapes



Branches will respond to wind

The junction exposed to wind exhibited increased radial growth, with an increase in latewood density on the upwind side and an overall decrease in microfibrilar angle (increase flexibility) when compared to a junction from a less exposed site.

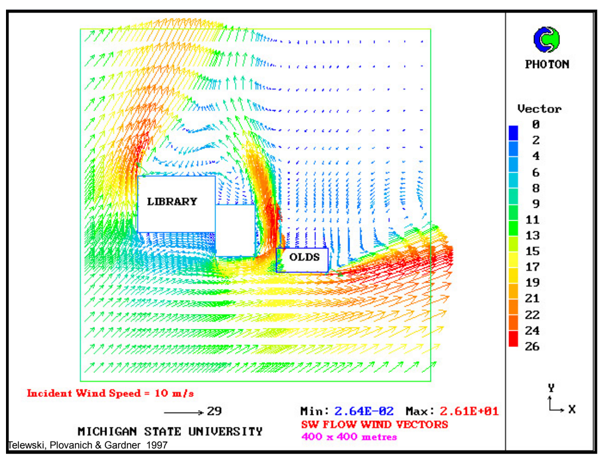
Jungnikl, Goebbels, Burgert & Fratzl 2009 Trees 23:605-610

Summary of structural changes in acclimation to windy environments

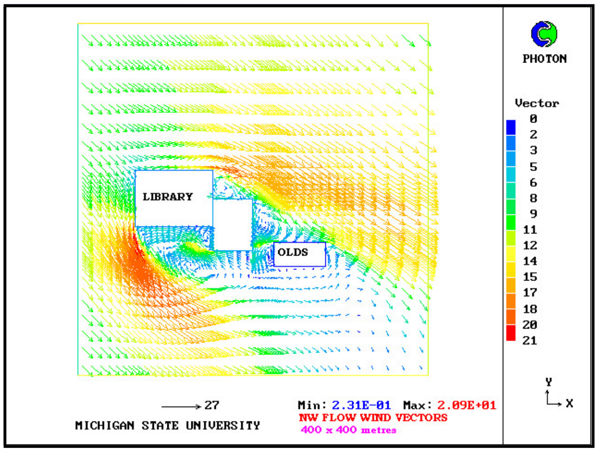
Anatomy
- Increase in MFA
- Increase in grain angle
- Increased cell division in direction of flexing (increase I)
- Increased wood density
- Increase lignification (increase S:G)
- Less stiff, more flexible

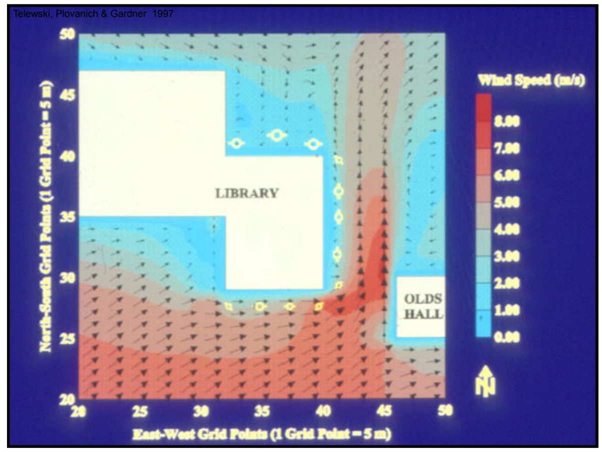
Morphology
- Lower H:D (shorter-thicker stems) taper
- Smaller leaves
- Shorter internodes
- Shorter branches
- Thicker branch junctions
- Streamlining
- Roots-

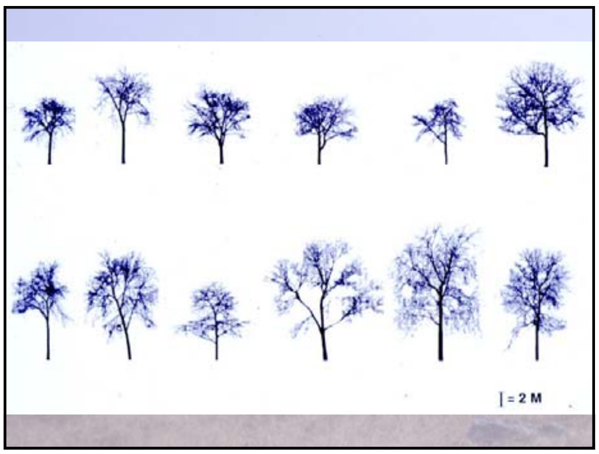
Applications in the Urban Forest

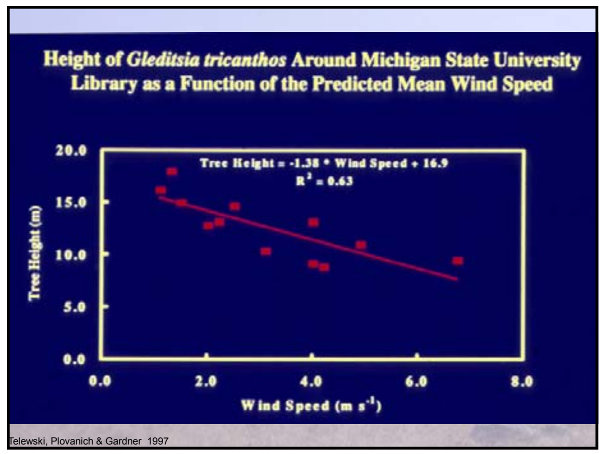


Telewski, Plovanich & Gardner 1997









Thank You
Questions?

Claude Monet's
Poplars, Wind Effect
1891

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MICHIGAN STATE UNIVERSITY

Tree Rings, Tree Growth, and Root Damage: What's the connection?

California Tree Failure Program
Filoli Center
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January 8, 2015

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In Memory of Thomas P. Harlan, Friend, Colleague, Mentor

Dendrochronology: the study of tree rings

- The study of accurately dated annual growth rings
- Used extensively in Archeology
- Used in reconstructing Climate
- Used in ecology and forestry
- Used in geology
- Can be applied in urban forestry/arboriculture

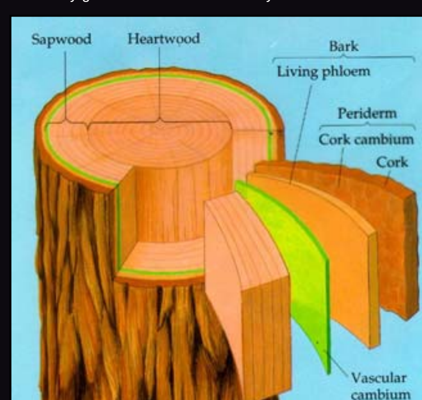
How does Dendrochronology Work?

- Establish the tree has tree rings
- Establish that tree rings are annual
- Tree rings are 'relatively' uniform around the circumference of the stem
  - ie. Some trees with extreme lobed or fluted stems are difficult to study
- There is year to year variability in some feature of the ring: width, density etc. Sensitivity.

What is an Annual Growth Ring?

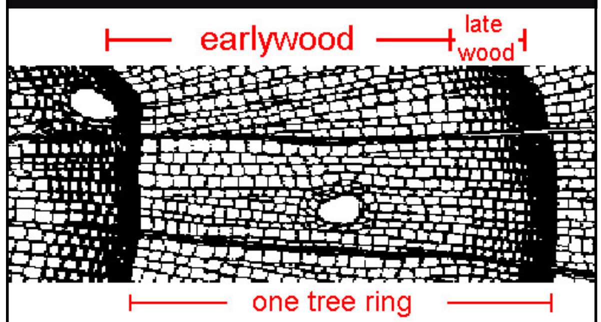
- Layer of wood produced by the Vascular Cambium every year, punctuated by a distinct change in cell morphology
  - EARLYWOOD
  - LATEWOOD
  - Conifers
  - Angiosperms
    - Ring porous
    - Diffuse porous
- Missing Rings?
- False Rings?

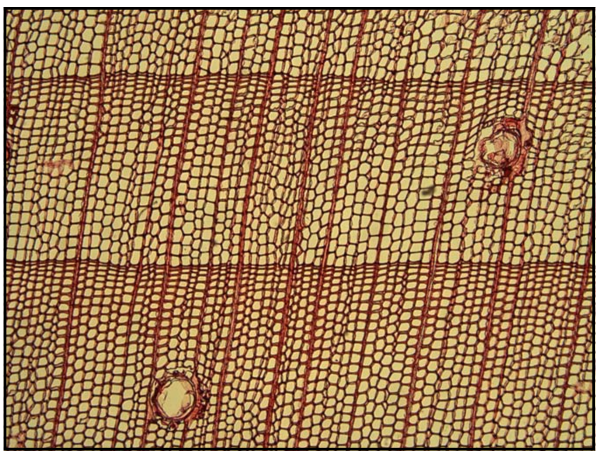
1. Typical secondary growth as seen in both dicotyledons and conifers



Conifer Growth Rings

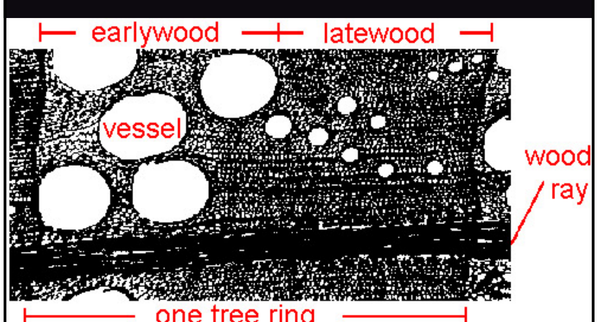
- Non-Porous
- lacking vessels
- have tracheids
- pines, firs, spruce, hemlock, Douglas fir, larch, cypress, dawn redwood, yew, cedar etc

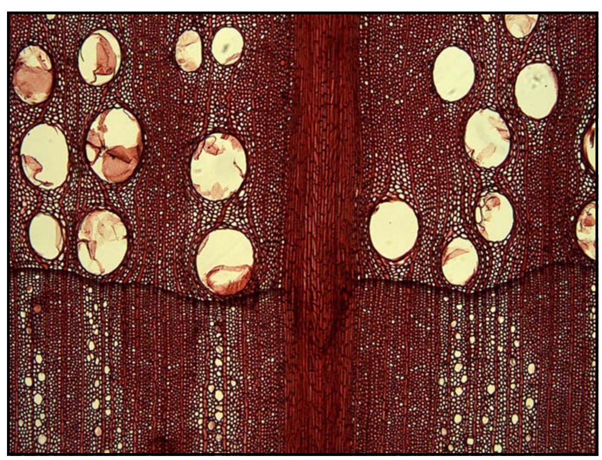




Broad-leafed Trees (Angiosperm) Tree Rings:

- Ring Porous,
  - large vessels in the earlywood
  - small vessels in the latewood.
- oak, ash, sassafras, sycamore





Broad-leafed Trees (Angiosperm) Tree Rings:

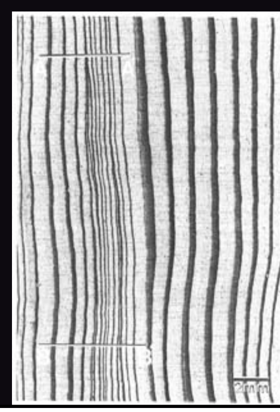
- Diffuse Porous-
  - Vessels uniform in diameter across the growth ring
  - Annual ring boundary a layer of thick-walled parenchyma cells
- Maple, poplar, walnut, magnolia

What is a Missing Ring?

My precious…..

How old is this tree? Can you rely on counting rings?

Coastal Redwood



10 rings

13 rings

Telewski and Lynch 1991

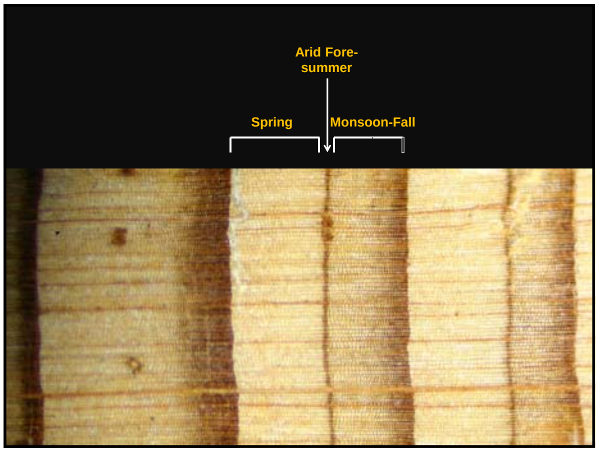
What is a False Ring?

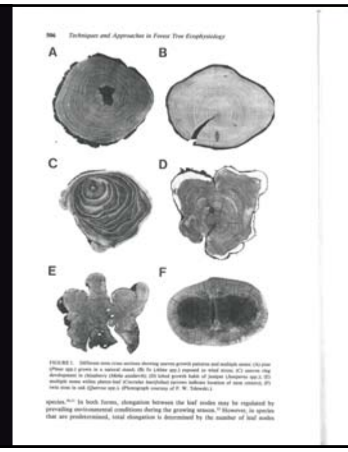
In the mountains of Southern Arizona:

Spring- Candle and initial needle expansion, soil moist from winter precipitation, growth regulators flow to stimulate cambium

Arid Fore-summer- Candle and needle expansion slow down due to dry conditions, growth regulator flow slows, cambial growth slows

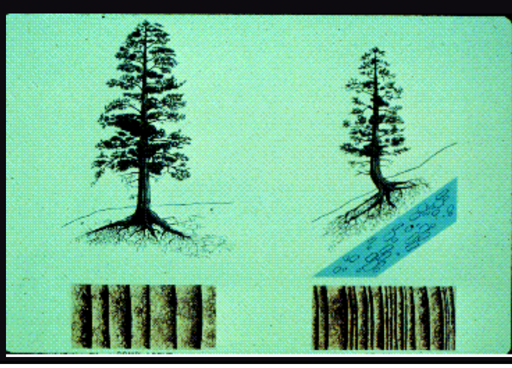
Summer Monsoon- return of precipitation reactivates candle expansion and needle maturation, flow of growth regulators resumes until end of growth season and shortening of days.





Telewski & Lynch 1991

Complacency vs. Sensitivity



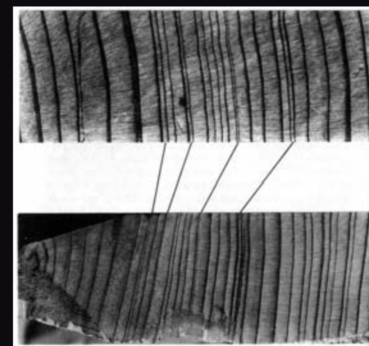
<u>**Field Sampling**</u>

- **Field gear**
- **Site selection**
- **Site description**
- **Field sampling designs**
- **Coring a tree**
- **Dealing with rotten wood**
- **Taking care of your increment borer**

Cross Dating Tree Rings

- Match the pattern of wide and narrow tree rings within the tree (along different radii)
- Match the pattern of tree rings between trees of the same species in the same area.
- The Skeleton Plot
- The Width Measurement Method
- Assign calendar years to individual rings

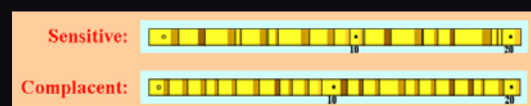
- Cross dating- Matching up the pattern of wide and narrow growth rings



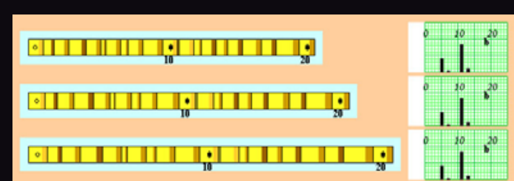
Skeleton Plotting; one method of cross-dating

- Visual comparison of neighboring growth rings and ranking them from zero to ten
- Very Wide = 0
- Very narrow to missing = 9 -10
- A moving average

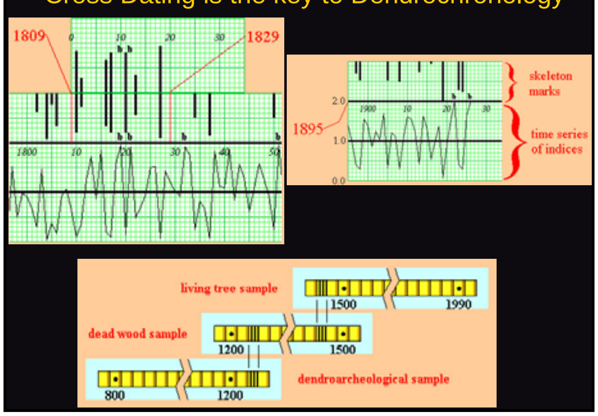
Year to year variations in ring characteristic

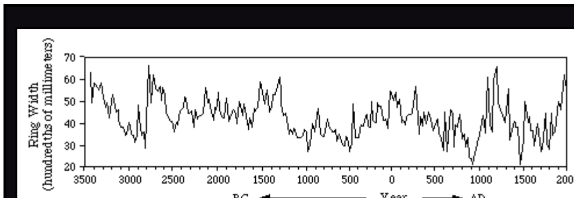


It's ok if some trees are faster growing than others



Cross Dating is the key to Dendrochronology

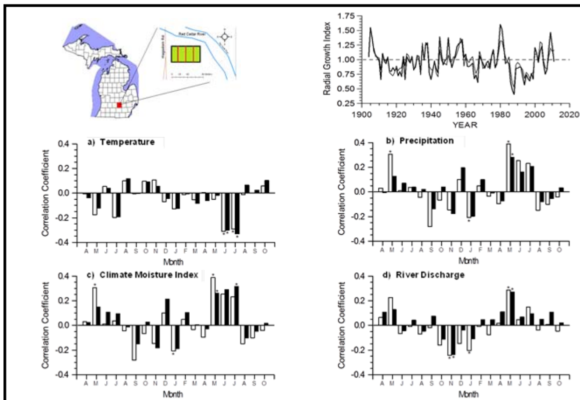




Dendrochronology

Ring-Width Analysis/Wood Density/Early-Latewood width

- Examples of dendrochronological studies
  - Micro-site analysis (Beal Pinetum)
  - Fire history reconstruction
  - Insect outbreaks and spread of invasive species
  - Root damage during construction impact on tree growth

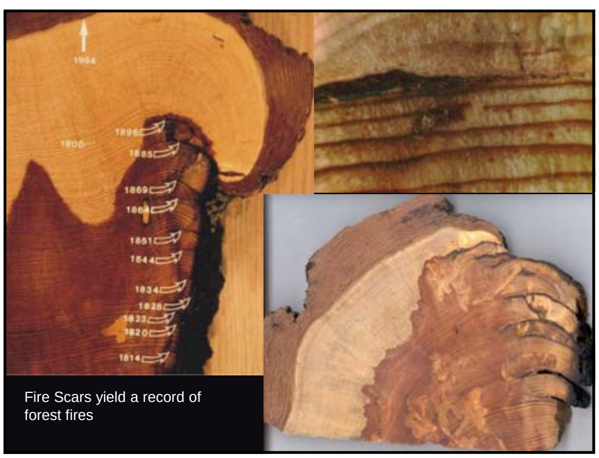


A monthly climatic moisture index is calculated by subtracting values of potential evapotranspiration (PET) from precipitation. The moisture index combines the effect of both precipitation and minimum and maximum monthly temperature on moisture regimes (Hogg 1997).

Chhin, Chumack, Dahl, David, Kurzeja, Magruder and Telewski. SUBMITTED. Growth-climatic relationships of *P. strobus* in the floodway vs. terrace forest along the banks of the Red Cedar River, Michigan. Tree Ring Research

Reconstruct and Date Disturbances, Injuries, Fires, Floods

Fire Scars yield a record of forest fires



Fire Scars yield a record of forest fires

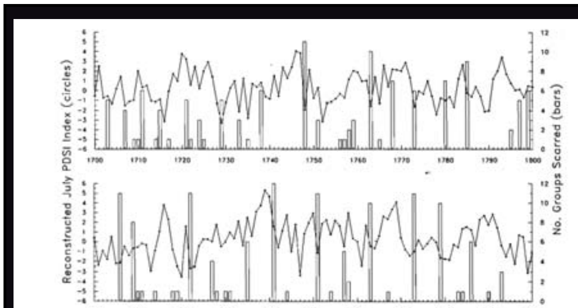


FIG. 8. A tree-ring reconstruction of the July Palmer drought severity (PDSI) index 1700–1900 versus the number of groups of trees recording a fire. All fire years are shown.

What does this figure tell you about fire frequency?

YES

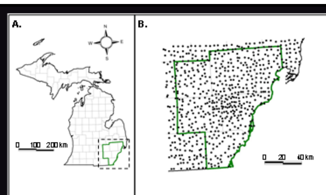
And

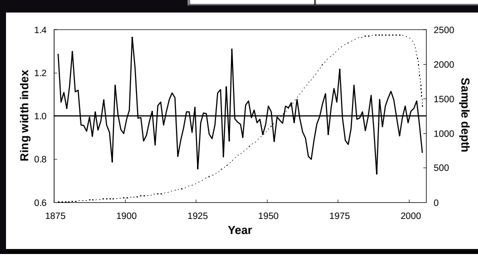
Pestilence

TOO

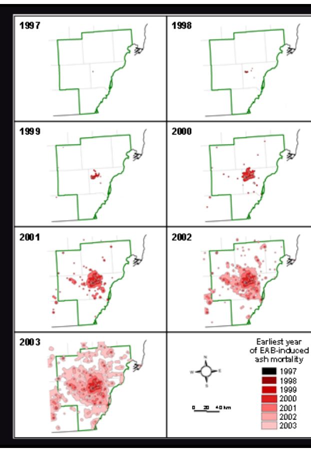
Epidemiology of the spread of the Emerald Ash Bore in Michigan

Siegert, N.W., McCullough, D.G., Liebhold, A.M. and Telewski, F.W. 2014. Dendrochronological reconstruction of the origin and progression of ash mortality caused by the invasive emerald ash borer. Diversity and Distribution





Interpolated reconstruction of the earliest *Agrilus planipennis* -induced ash mortality across study area. Initial 2002 quarantine area denoted by the green outline.



The Effects of Mechanical Trenching on Secondary Growth of Trees

Dr. Frank W. Telewski, Robyn Ast
Jason Kilgore
Department of Plant Biology

Location

- On the banks of the Red Cedar, Michigan State University

History of the Site

- In 1993, a construction company began work to install new lamp posts along the Red Cedar River
- A 30 inch deep trench was dug with a mechanical trencher approximately 1 ft from existing sidewalk, on the river side.

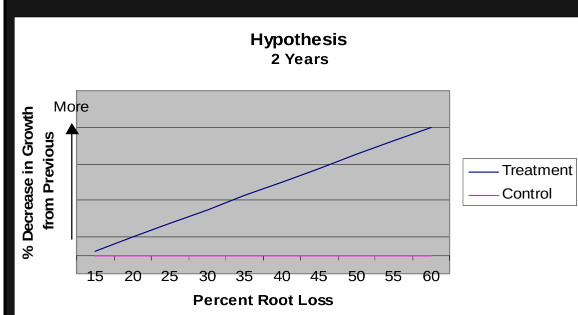
History Cont.

- Trench was 500 feet in length and affected 16 mature trees
- Trench was of varying distance from existing trees
  - Closest distance approximately 5 feet from trunk

Hypothesis

- Mechanical trenching in the root zone of a tree causes a measurable decrease in radial (secondary) growth.
- Decrease in secondary growth is in proportion to proximity to disturbance site.

Hypothesis



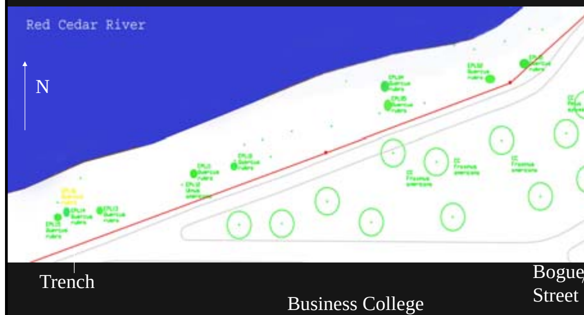
Overview of Tree Growth

- Primary growth of a tree adds height
- Secondary growth of a tree adds width
- Each year, in most climates, trees add a ring of growth
- Rings can be cross-dated and measured

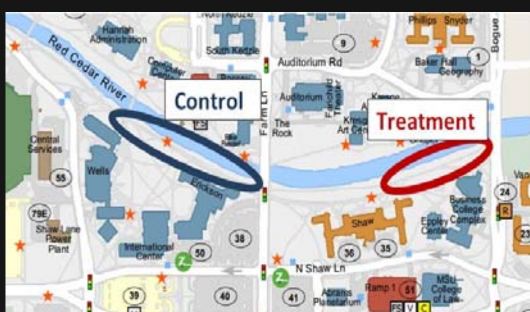
Cores used in this study:

- This study only examined the *Q. rubra* samples
  - 38 samples:
    - 18 treatment
    - 20 control

Treatment Sample Location



Map shows location of the Treatment and Control tress on the MSU campus.

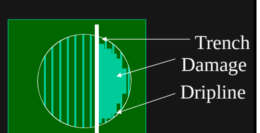


Forestry Survey Criteria

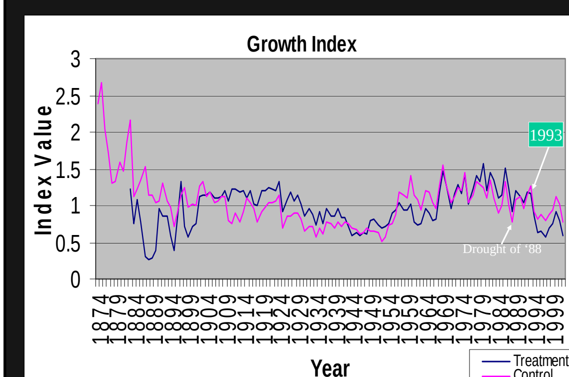
- Trees examined for:
  - Roots
  - Soil compaction
  - Presence of insects and disease
  - Trunk
  - Scaffold Branches
  - Smaller branches and twigs
  - Leaves

Forestry Survey Results

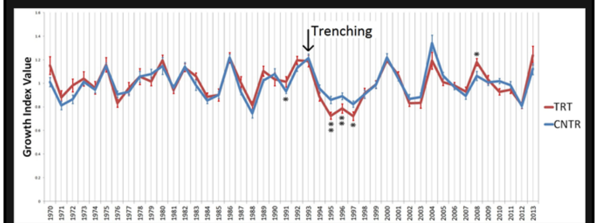
- 1993 - Percent of Root Loss determined
  - Varying from 6% to 41%



- 1995 - All trees (except the old sycamore) found in general good health
- 1996 – All trees (except sycamore) found in general good health, slight decrease in twig growth of 11 trees



Tree Ring series from 2014 study: 20 years after damage



Level of Significance
*P = 0.05
**P =0.01

Conclusions

- Trenching had a negative impact on secondary growth
- In 2003 study, the effect of the damage had yet to decrease
- In 2014 study, the effect of the damage only lasted for 5 years.
- Decrease in secondary growth was more significant with greater root loss

Implications

- The tree protection policy implemented Campus Park and Planning and Physical Plant is necessary
- The allowable distance for trenching from an existing tree trunk should be no less than the dripline
- Standard Forestry surveys are not the best method to evaluate the impact of root damage on tree health

Where to go for more information:

- http://www.LTRR.Arizona.EDU/labinfo.html
- *An Introduction to Tree-Ring Dating*, M.A. Stokes & T.L. Smiley
- *Tree Rings and Environment. Dendroecology*. 1996 Schweingruber, F.H.
- *Tree-Rings and Climate.* 1977 H.C. Fritts
- *Tree Ring Analysis : Biological, Methodo-logical, and Environmental Aspects* 1998. R. E. Vetter, R. Wimmer (Editors)