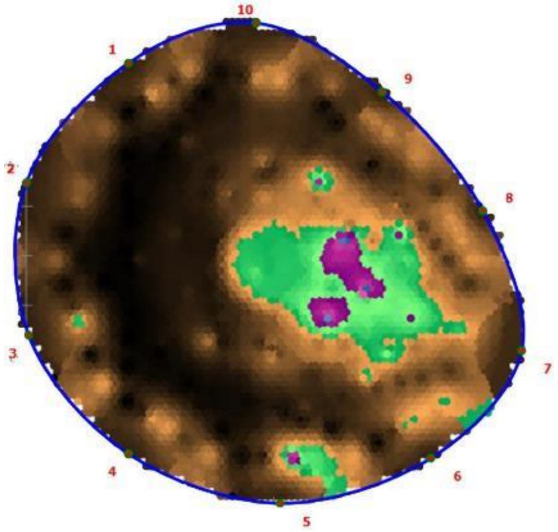
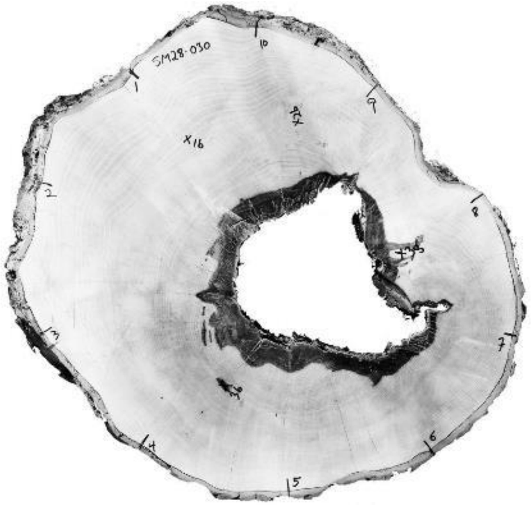
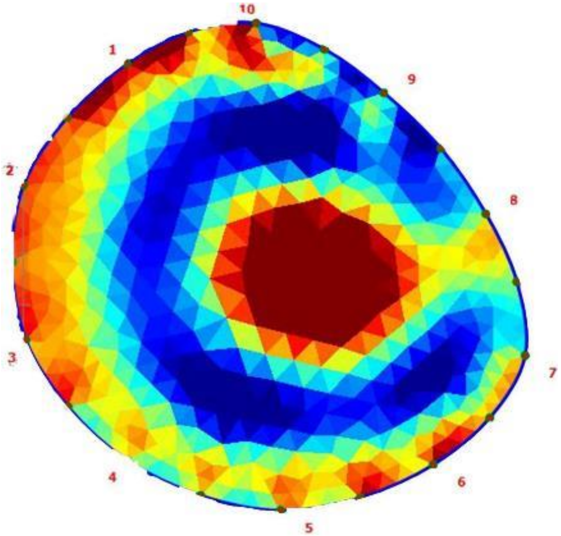
Accurately accounting for decay and carbon loss in trees:

a novel nondestructive approach using tomography







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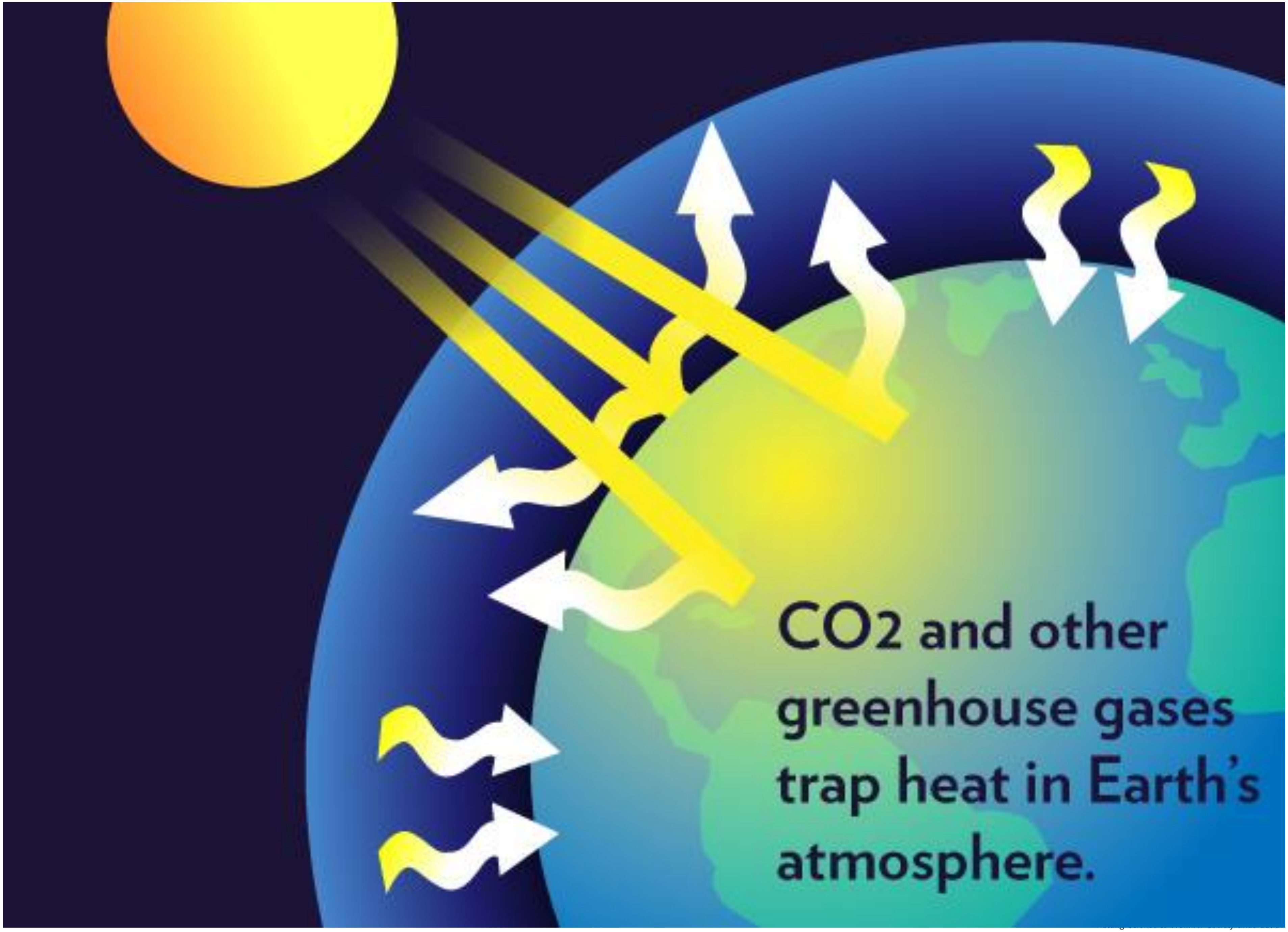
Overview

- Background
- Tree Tomography: what is it, how it works
- Assessing internal decay: methodology
  - Qualitative assessment
  - Quantitative assessment
  - Validation
- Summary



CO2 and other greenhouse gases trap heat in Earth's atmosphere.

Atmospheric Carbon

- Fairly stable at 260-280 ppm for ~10,000 years.

- Began to increase at the dawn of the industrial revolution (~1750).

- Currently at >400 ppm;
  - ~30% higher than at *any* time in the last 650,000 years.

SPECIAL REPORT THE LIFE AND TIMES OF THE COLORADO RIVER

onearth

BEHOLD, THE CARBON EATER

New science explains how forests could help save us from global warming

NRDC | SPRING 2008
WWW.ONEARTH.ORG

Spring 2008

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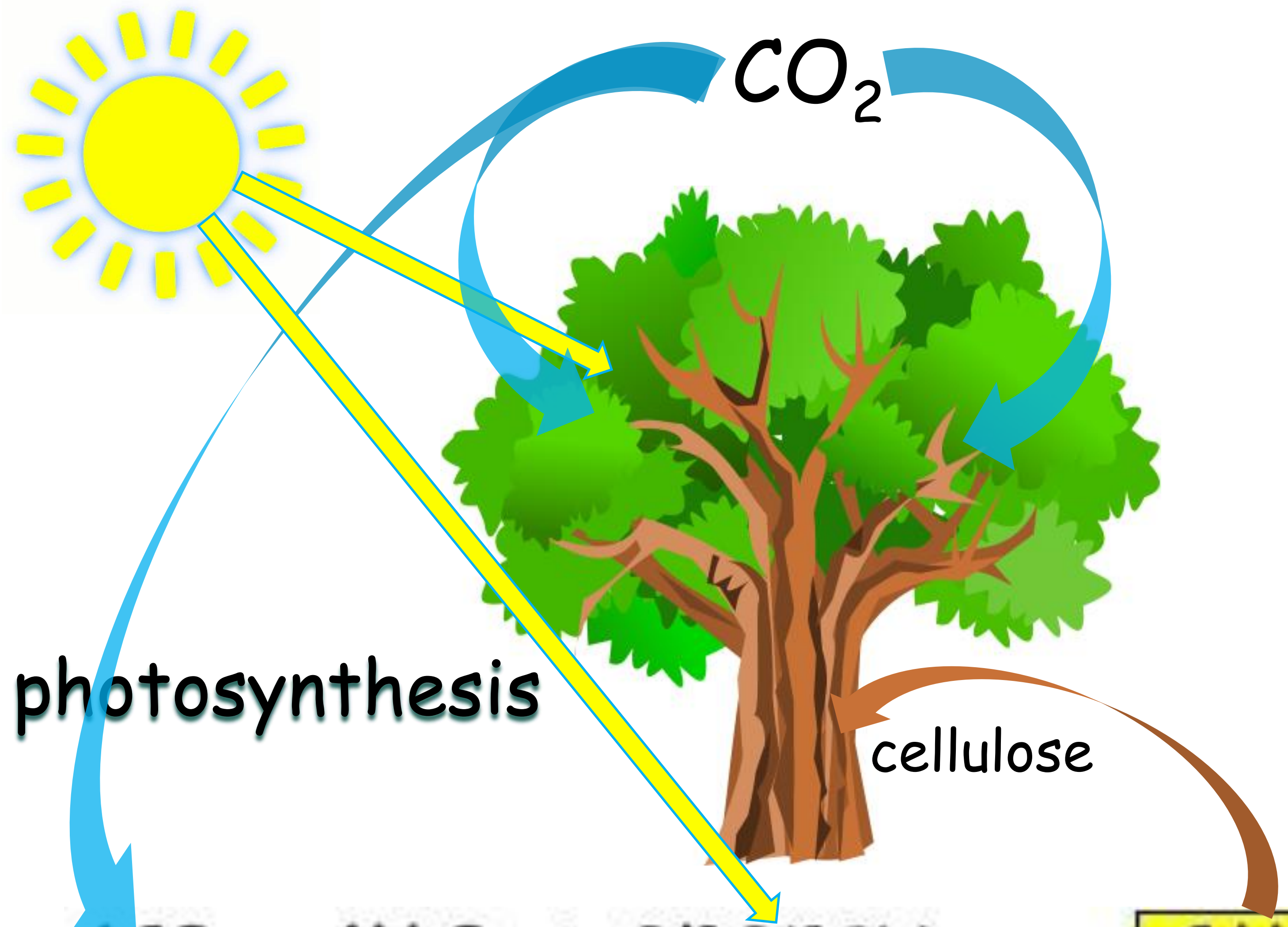
Carbon cycling in trees

- Carbon sequestration through photosynthesis:

  Atmospheric CO_2 → → → wood

- Carbon *“de-sequestration**”*:
  - Decomposition (e.g., leaf litter)
  - Internal decay:
    - Wood metabolized by fungi and bacteria;

    wood → → CO_2 → atmosphere.



CO_2

photosynthesis

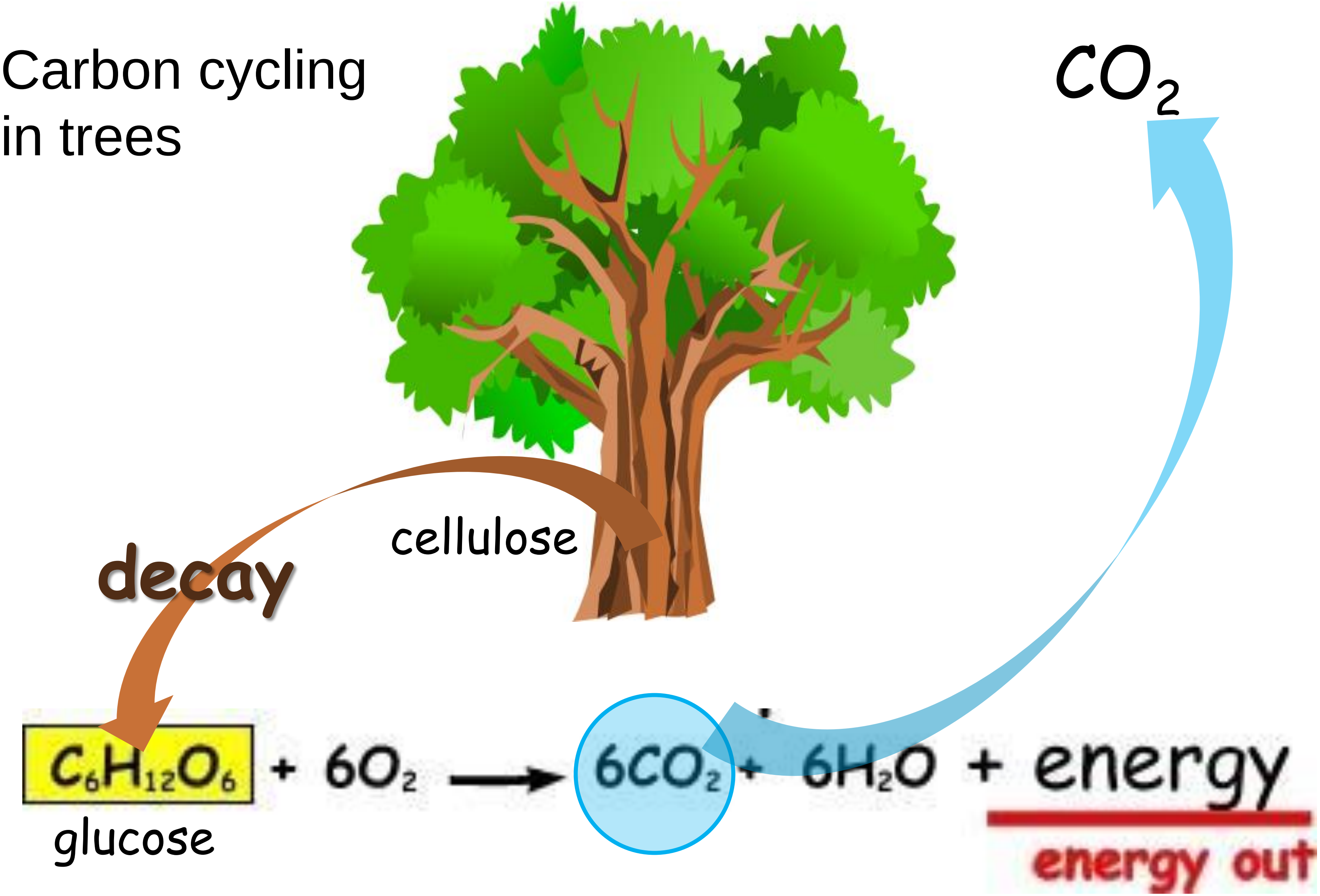
cellulose

$$6CO_2 + 6H_2O + \underline{energy} \rightarrow \boxed{C_6H_{12}O_6} + 6O_2$$

energy in

glucose

Carbon cycling in trees



CO_2

cellulose

decay

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

glucose

energy out

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DECAY HAPPENS

Internal decay in forests

- *Quantitative data on internal decay:*
  - Extent and magnitude of internal decay in forests;
  - Quantitative impact on forest biomass estimates.

- ***Improve our understanding of role forests play as C sinks.***

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Internal decay in forests

<u>Objective</u>

- Develop a tomography-based methodology for quantifying internal decay in trees;
  - More accurate estimates of sequestered above-ground carbon.

Assessing Internal Decay with Tomography

Tomography

Imaging by section, through the use of any kind of penetrating wave.

Assessing Internal Decay with Tomography

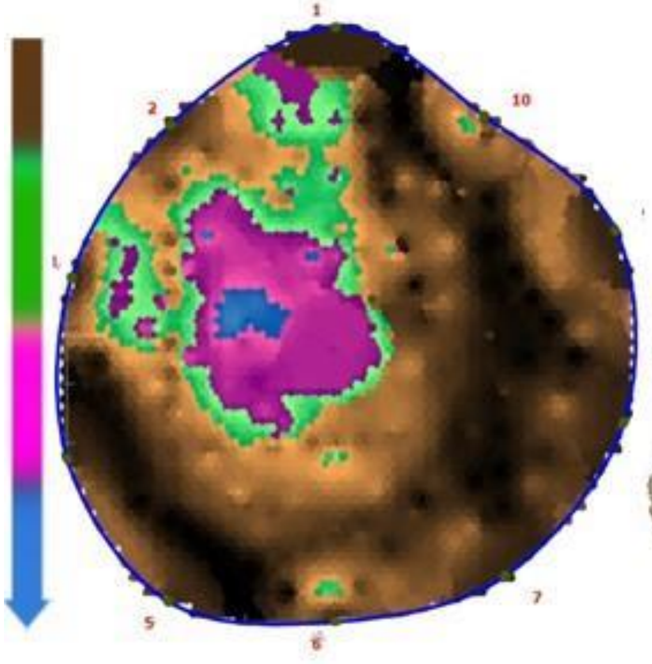
- ***Sonic Tomography (SoT)***
  - Velocity of sound is directly proportional to wood density;
    - Fastest through non-decayed (dense) wood;
    - Slower through decaying (less dense) wood;
    - Slowest through cavities.

Sonic Tomography

Velocity of sound is directly proportional to wood density

Fast = dense
= no decay

Slow = less dense
= decaying
or decayed (cavity)



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Assessing Internal Decay with Tomography

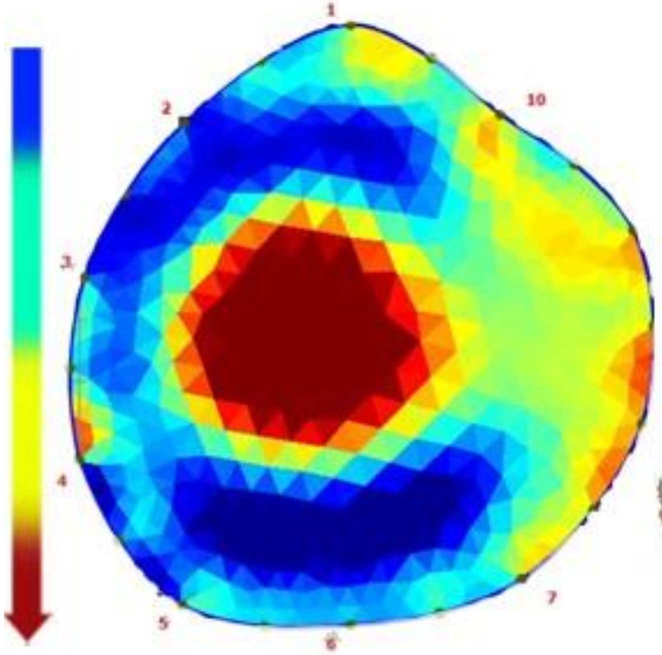
- ***Electrical Resistance Tomography (ERT)***
    - Electrical current varies with anything that alters the electrical field; e.g. water, ions.
    - Wet wood (e.g., wood undergoing decay) carries current faster than dry (non-decayed) wood.

Electrical Resistance Tomography

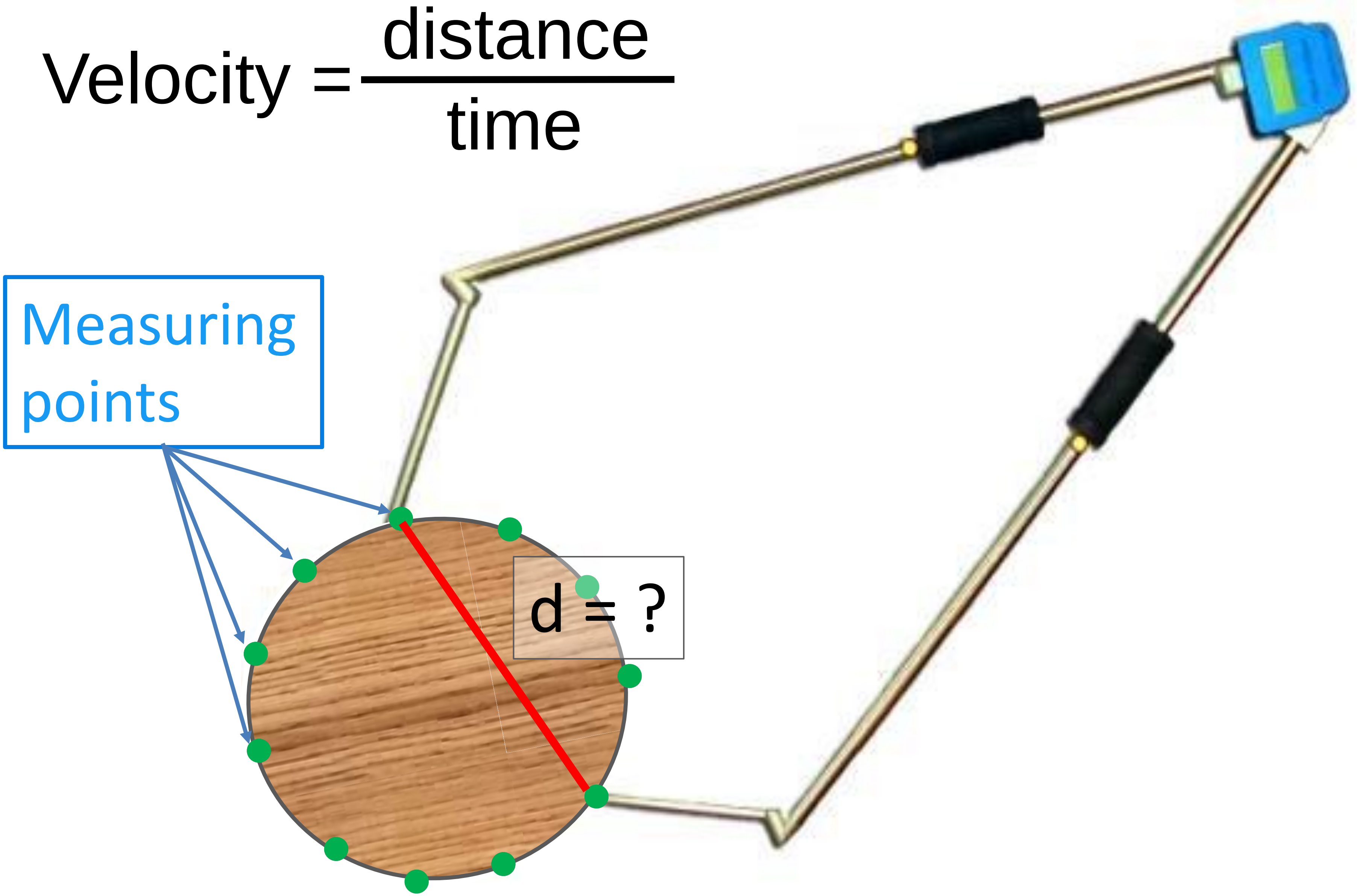
Wet wood (e.g., wood undergoing decay) carries current faster than dry (non-decayed) wood

Low = high water content
= incipient/active decay?

High = low water content
= sound wood
OR cavity



$$\text{Velocity} = \frac{\text{distance}}{\text{time}}$$



Measuring points

d = ?

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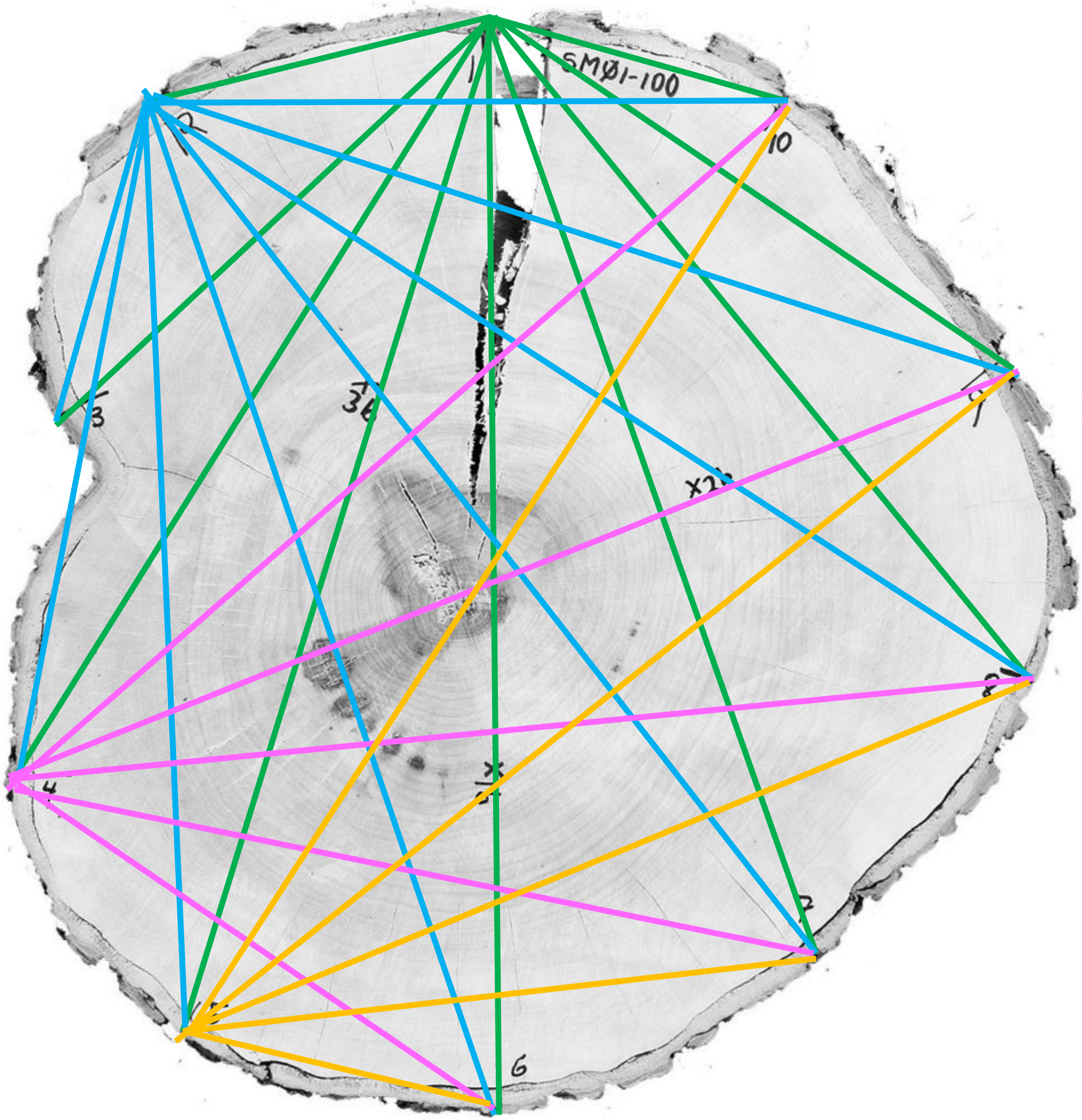
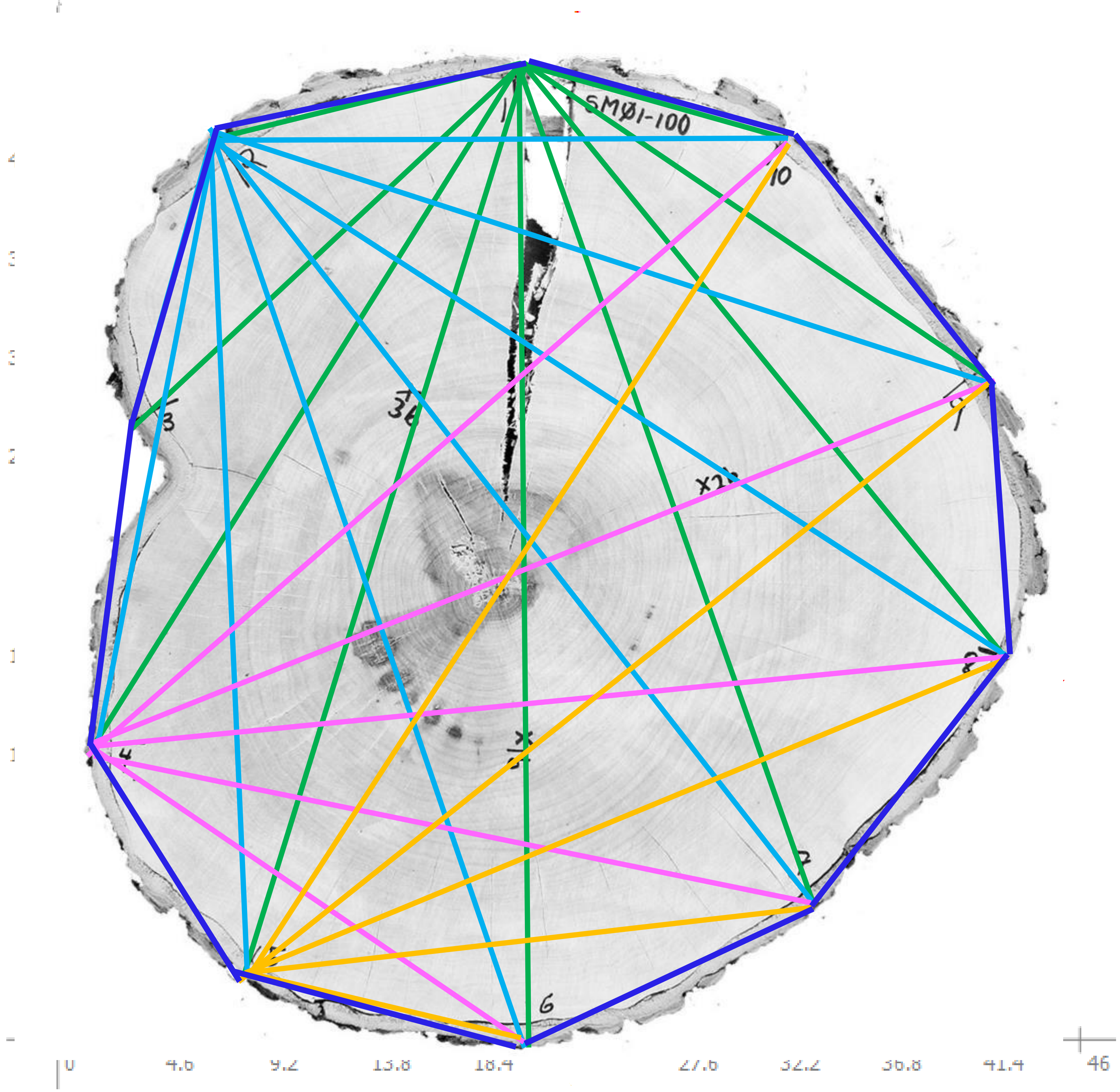
7
8
9
10
11
7
8
9
10


1
SM01-100
10
2
3
3b
9
x2b
8
4
x
7
5
6



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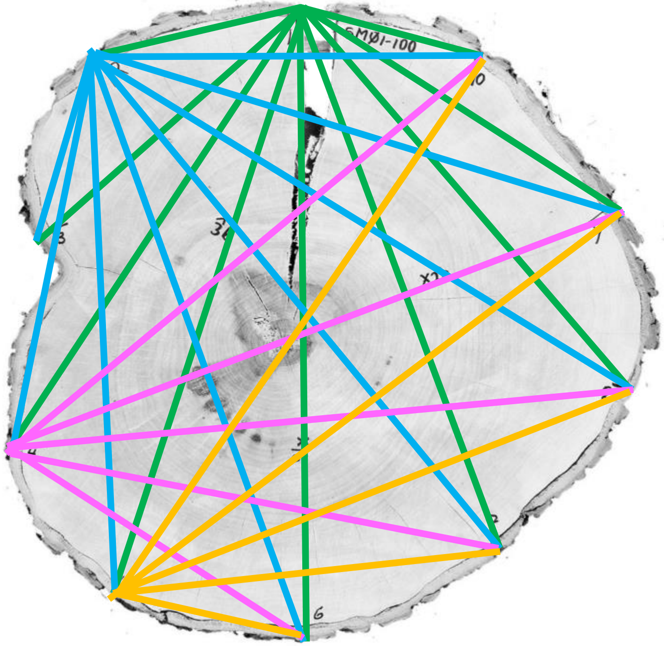

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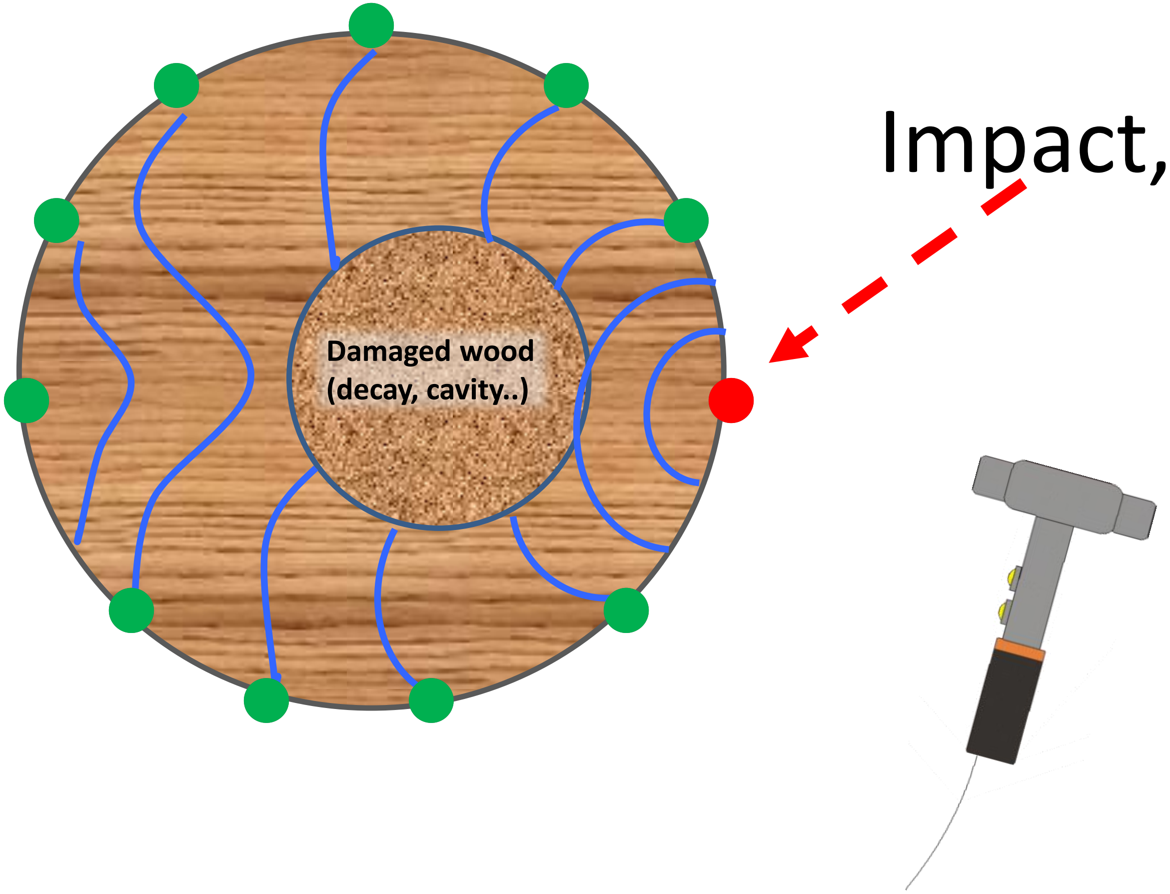
Sonic Tomograph
(SoT)

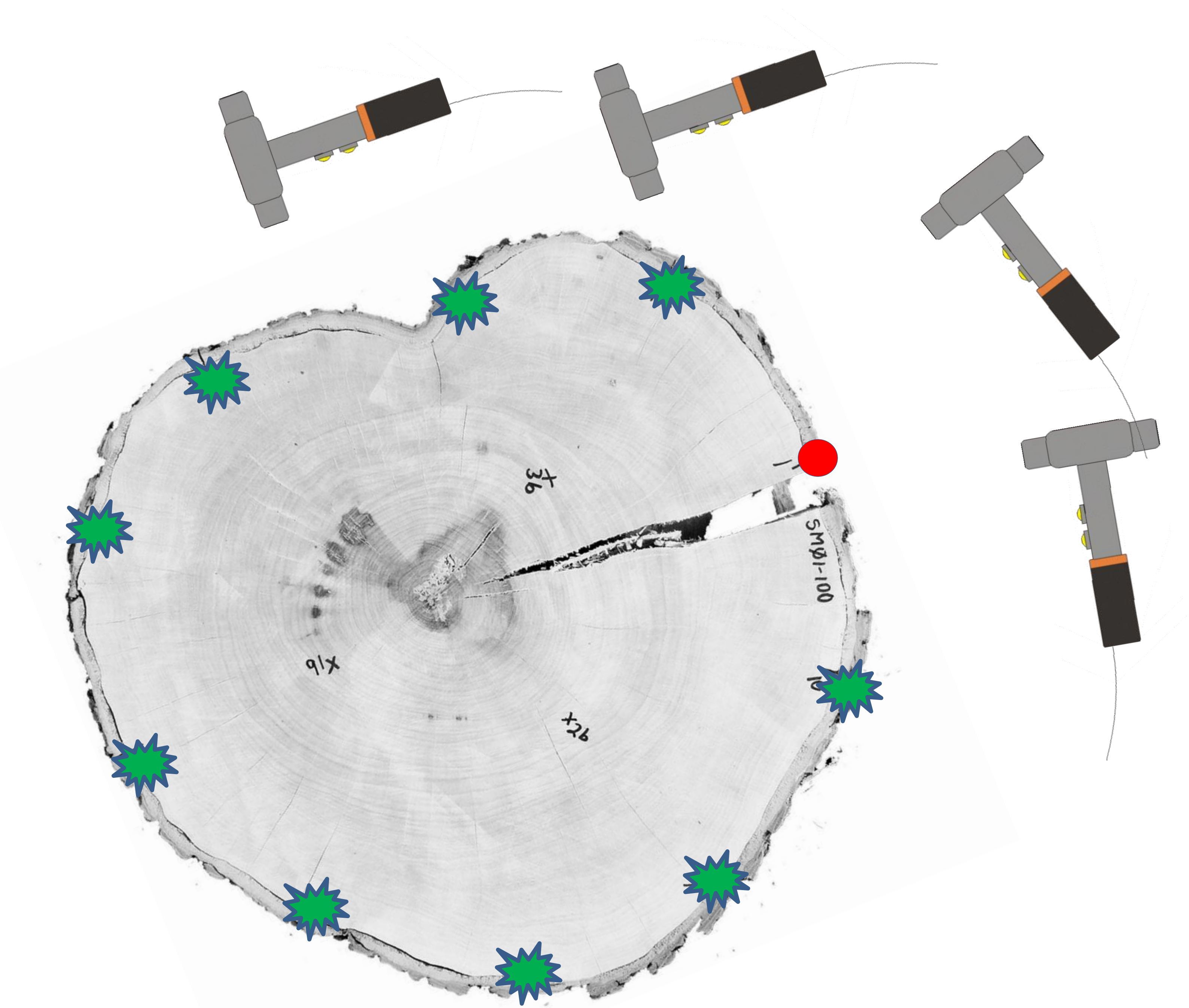
Electrical Resistance
Tomograph
(ERT)

Sonic Tomography

Where do sound waves travel ***SLOW*** (decay) relative to where they travel ***FASTEST*** (no decay)?




PiCUS³ Sonic Tomograph
5
4


x36
x16
x26
SM01-100
10

Assessing tomography

Qualitative:

- Visual assessments of how well tomography predicts internal condition;

Quantitative:

- Indirectly estimate C content using tomographic data;
  - Validate by comparison with direct mass-based estimate.

- Summer 2014
- Great Mountain Forest, Norfolk, CT
  - Late successional forest
- Three principle northern hardwood species:
  - Sugar maple, yellow birch, American beech
- 18-24 trees of each species
  - 2-4 tomographic cross-sections per tree
  - Fell trees; cut “cookies” at each cross-section
- Validate/calibrate methodology

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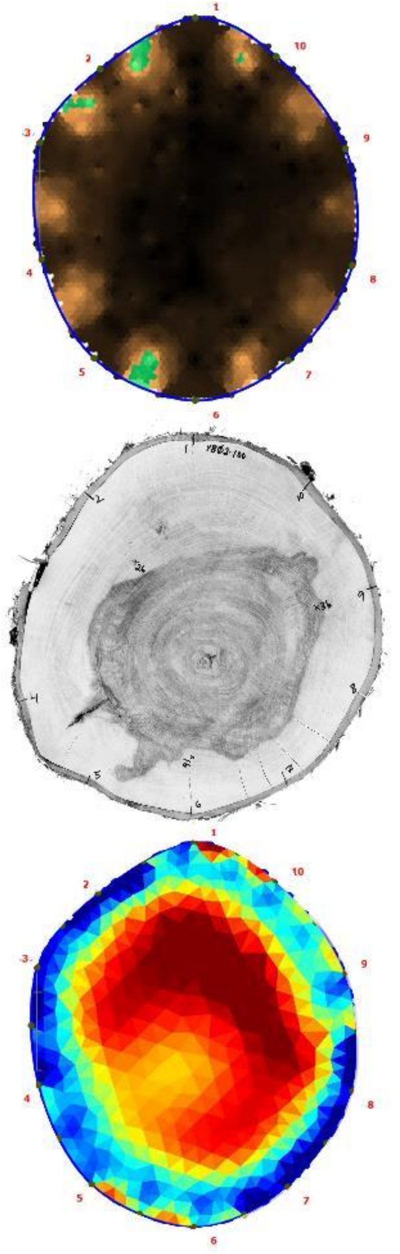
RANGER

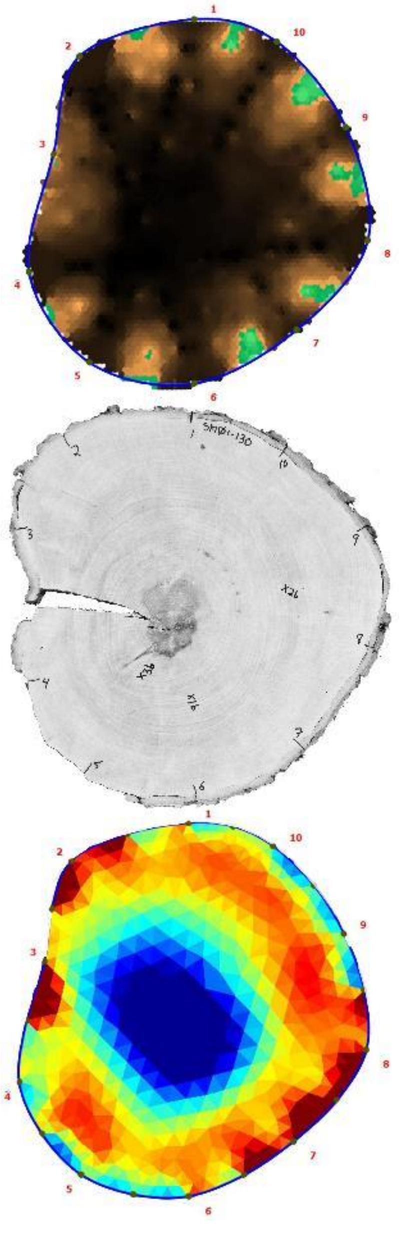

S22-1


GREAT
MOUNTAIN
FOREST
NORFOLK, CONN.
A13
10

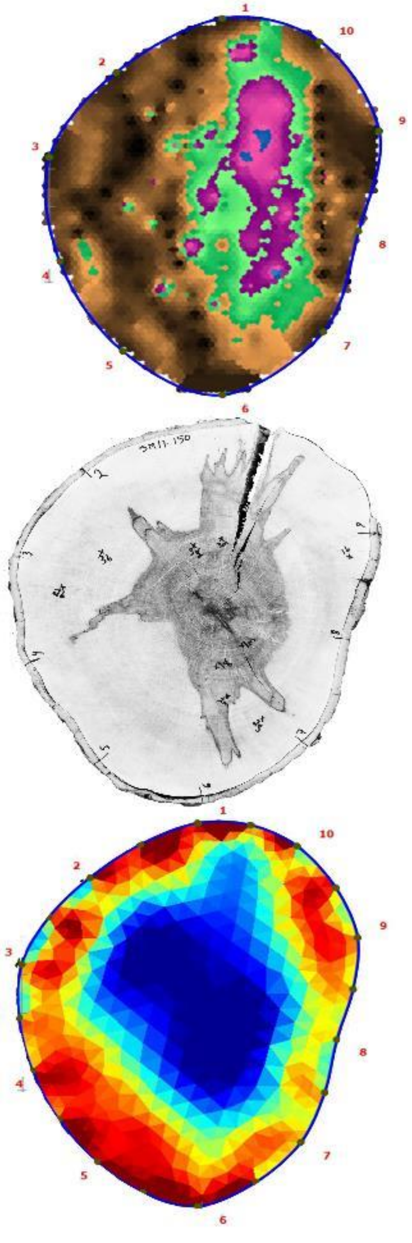
	# Trees Tomographed	**# Trees Felled**	**# Cookies**
American Beech	28	16	47
Sugar Maple	25	14	33
Yellow Birch	28	11	26
Total	81	41	106



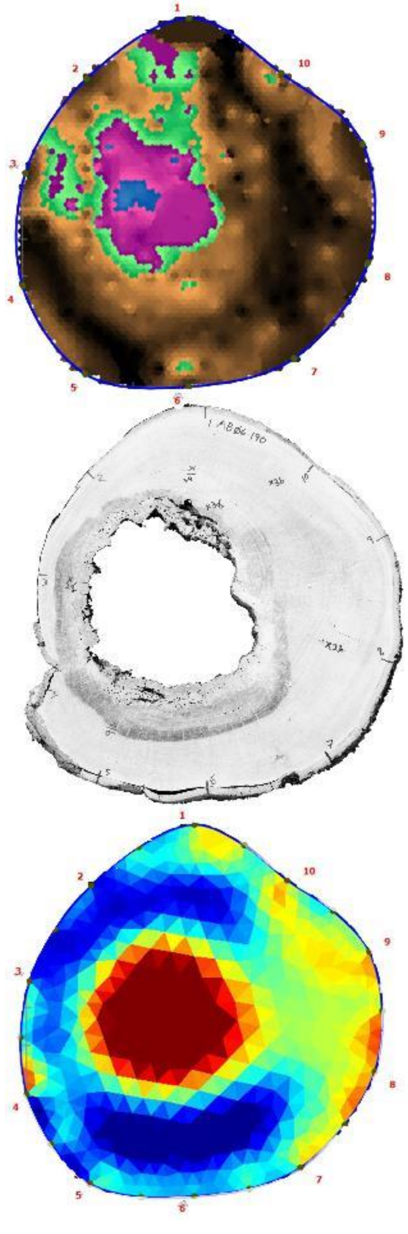
NO DECAY



INCIPIENT DECAY

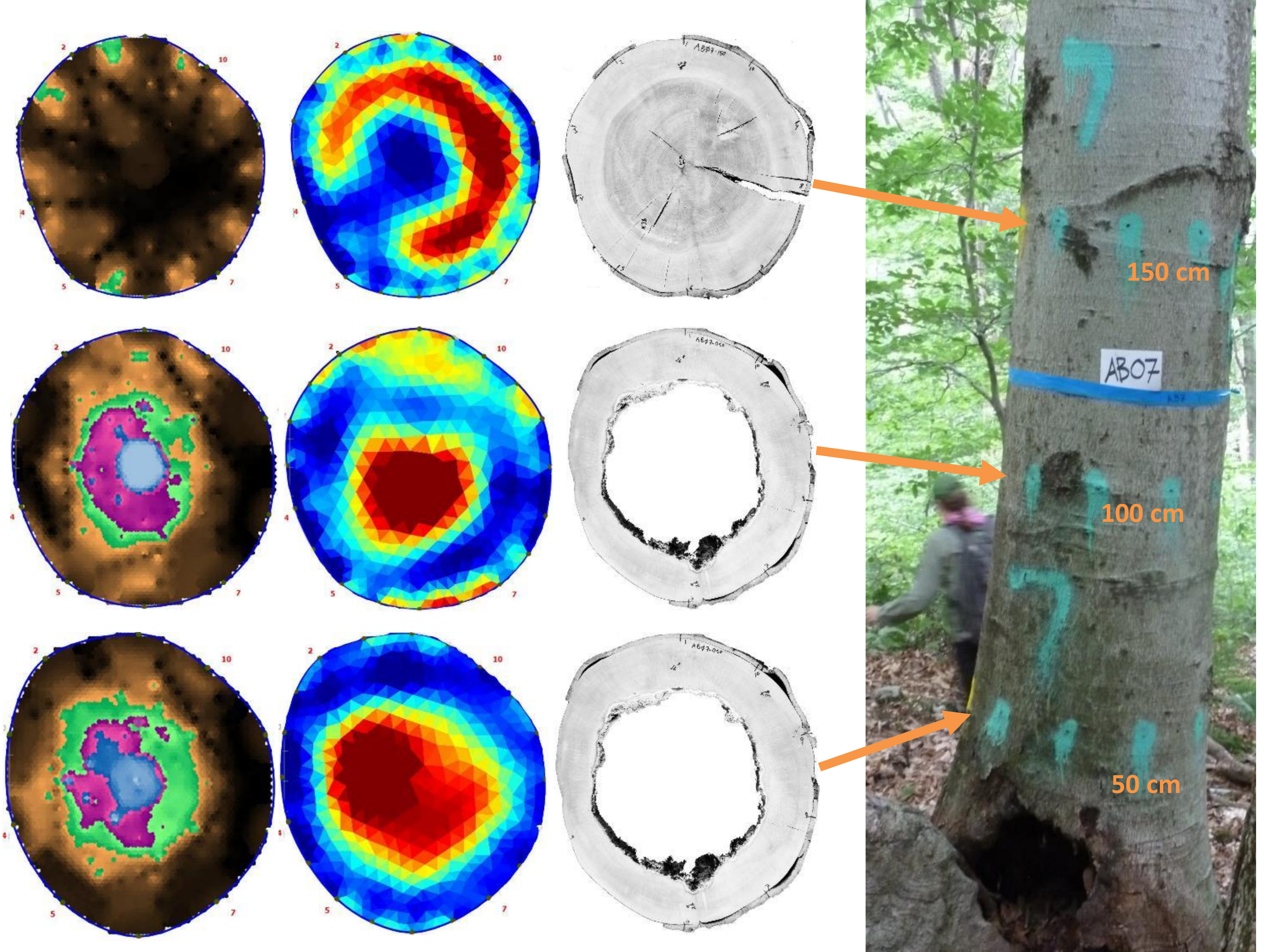


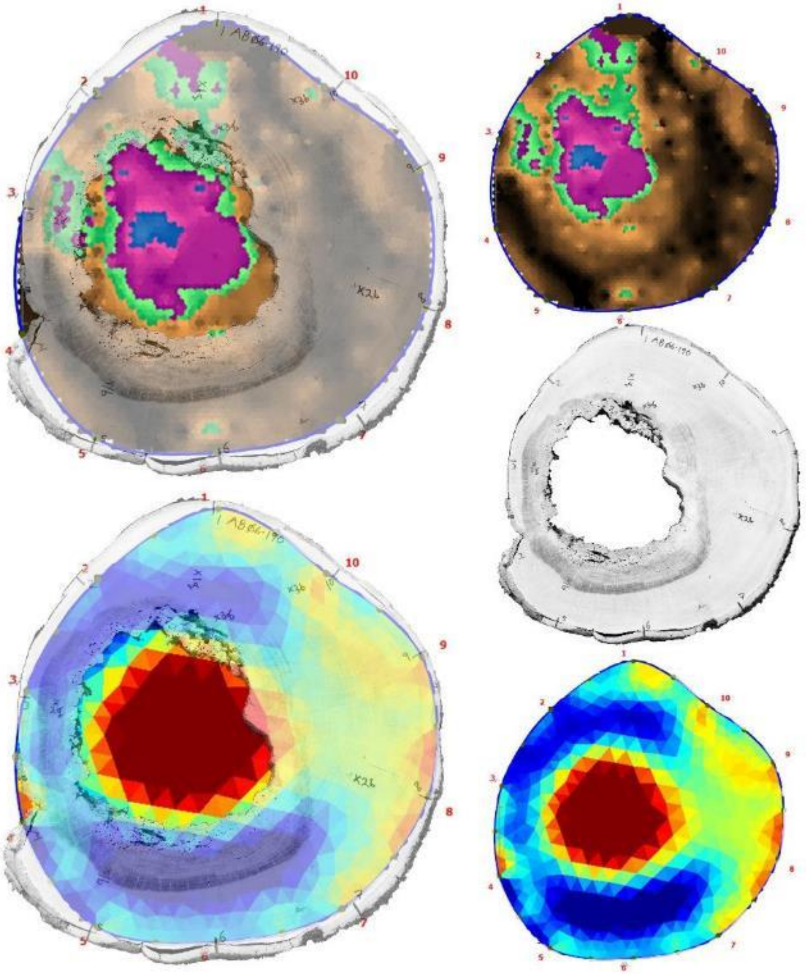
ACTIVE DECAY



CAVITY

	SoT		ERT		Predicted Internal Condition	C Density
	Color	Density	Color	Moisture		
A	brown	maximum	red	none	**No decay**	$[C]_{brA}$
B	brown	maximum	non-red	present	**Incipient decay**	$[C]_{brB}$
C	non-brown	reduced	non-red	present	**Advanced decay**	$[C]_{nbr}$
D	non-brown	reduced	red	none	**Cavity**	$[C]_{cav}$


2
10
4
5
7
AB07
150 cm
100 cm
50 cm



Qualitative Assessment of Tomography	
No decay	10/10
Active decay	36/36
Cavities	26/37
Misidentified as active decay	11
Total	95/106

Quantitative Assessment of Tomography

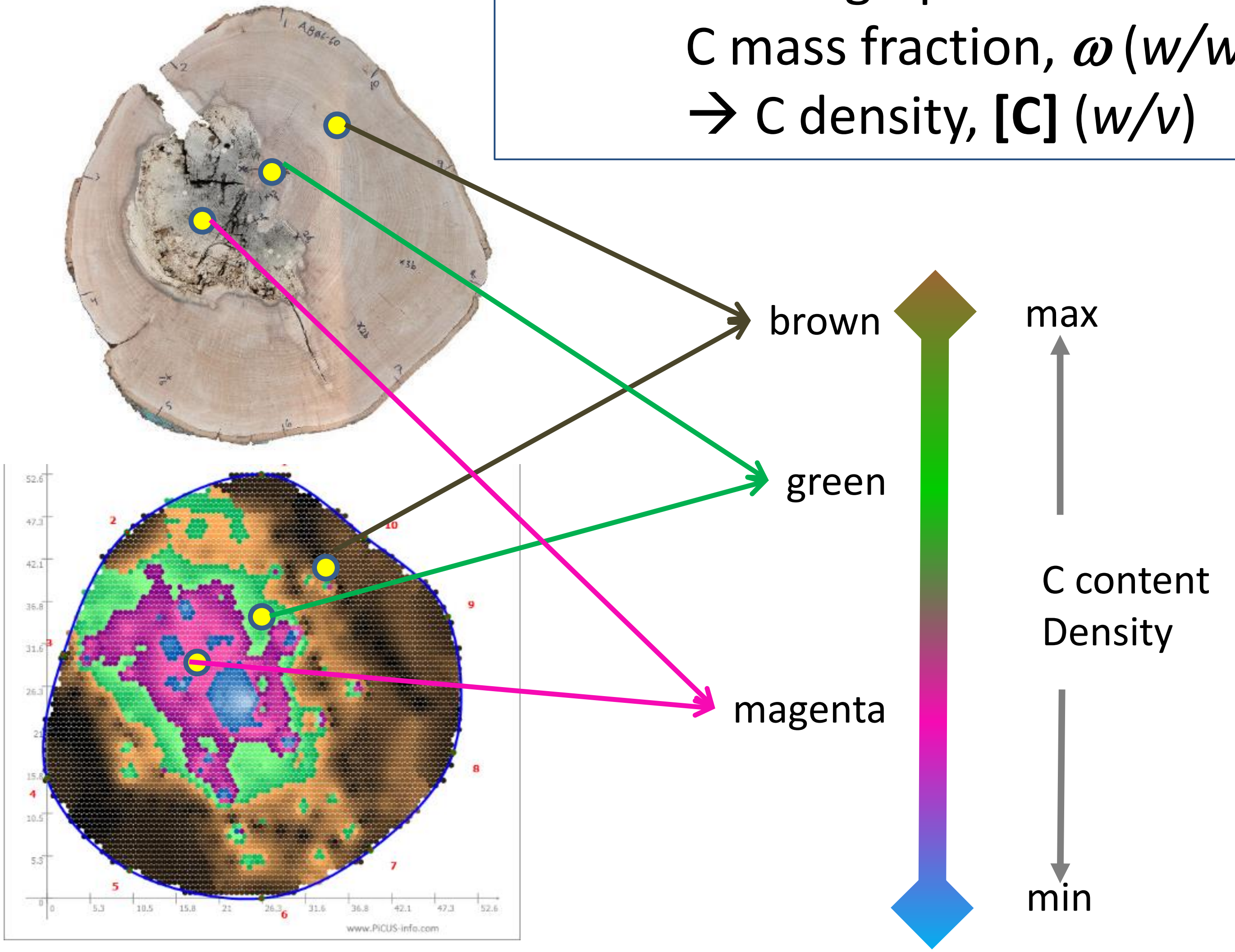
- Use tomography to indirectly estimate C content;
- Validate by comparison with a direct mass-based estimate.

Quantitative Assessment of Tomography

Gas Chromatographic Elemental Analysis (GCEA)

C mass fraction, ω (*w/w*)

→ C density, **[C]** (*w/v*)



brown

green

magenta

max

C content Density

min

508 Samples
Each Sample:
- Volume
- Mass

GCEA:
ω (% C)

508 Samples

Each Sample:

  - Volume
  - Mass

GCEA:

ω (% C)

Mass Fraction (ω) by SoT Category

ω (std dev)								
	American Beech		Sugar Maple		Yellow Birch		All Trees	
	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$
Brown	143	48.68 (0.52)	107	48.67 (0.49)	78	48.64 (0.70)	328	48.67 (0.56)
Green	58	48.67 (0.73)	36	48.41 (0.57)	21	49.10 (0.73)	115	48.67 (0.74)
Magenta	28	48.46 (0.39)	27	48.41 (0.71)	10	49.07 (0.98)	65	48.53 (0.68)
Combined	229	**48.65** (0.57)	170	**48.57** (0.56)	109	**48.76** (0.78)	508	**48.65** (0.62)

C Density, [C] (w/v) by SoT Category

$$[C] = \omega * M(\mathrm{g}) \div V(cm^3)$$

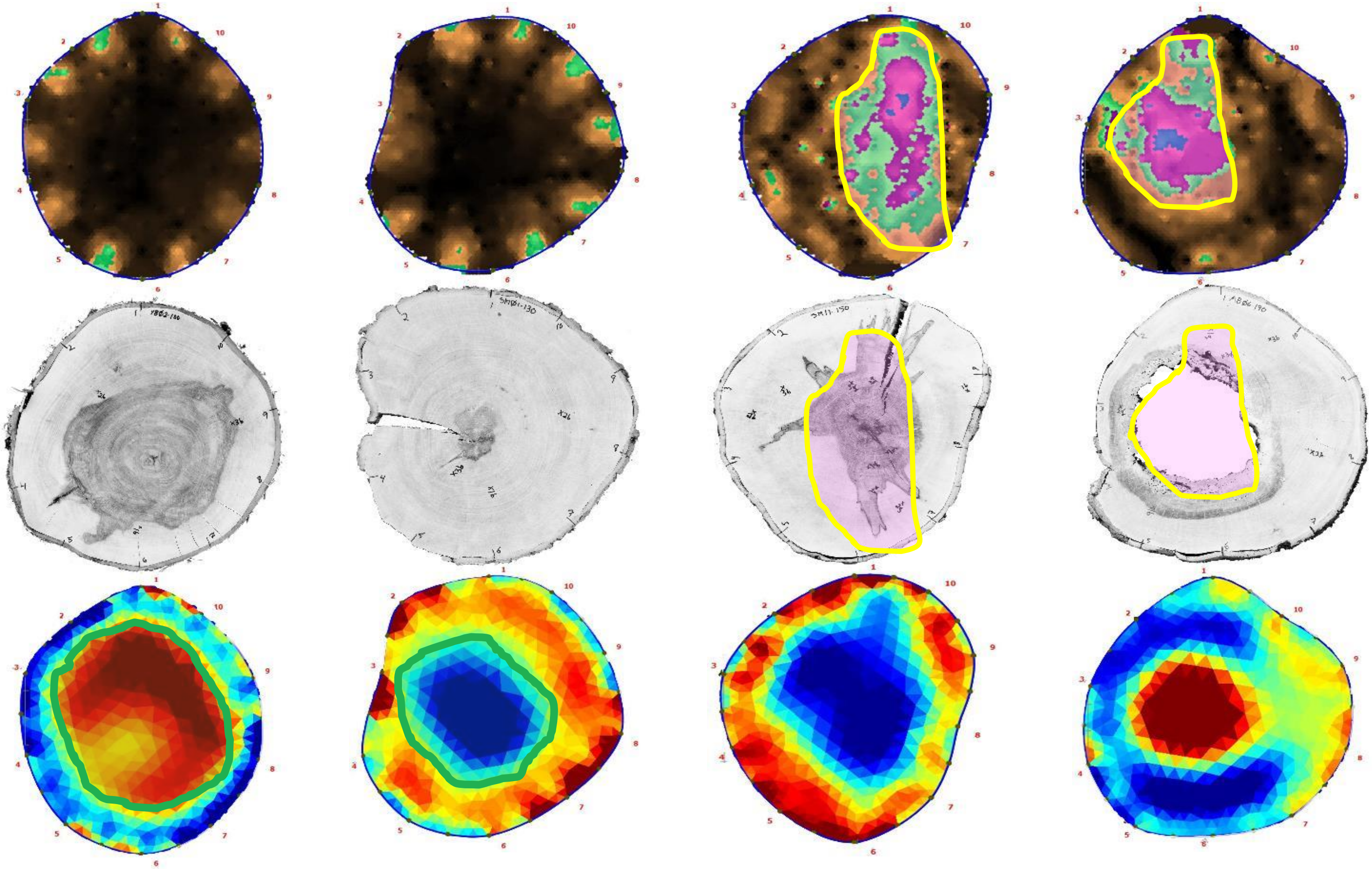
$[C]$, g/cm^3						
	American Beech		Sugar Maple		Yellow Birch	
	n	$\bar{x}$ (sd)	n	$\bar{x}$ (sd)	n	$\bar{x}$ (sd)
Brown, $[C]_{br}$	158	**0.35** (0.04)	96	**0.32** (0.04)	84	**0.32** (0.03)
Non-brown*, $[C]_{nbr}$	61	**0.23** (0.09)	31	**0.25** (0.10)	21	**0.26** (0.07)
ANOVA (F, *p*)	96.8, <0.001		17.4, <0.001		20.1, <0.001	

*Non-brown = Green + Magenta

C Density, [C] (w/v)

$$[C] = \omega * M(\mathrm{g}) \,/\, V(cm^3)$$

C Densities [C], g/cm^3			
	$[C]_{br}$	$[C]_{nbr\text{-}dec}$	$[C]_{nbr\text{-}cav}$
American Beech	0.35(0.04)	0.23(0.09)	0
Sugar Maple	0.32(0.04)	0.25(0.10)	0
Yellow Birch	0.32(0.03)	0.26(0.07)	0

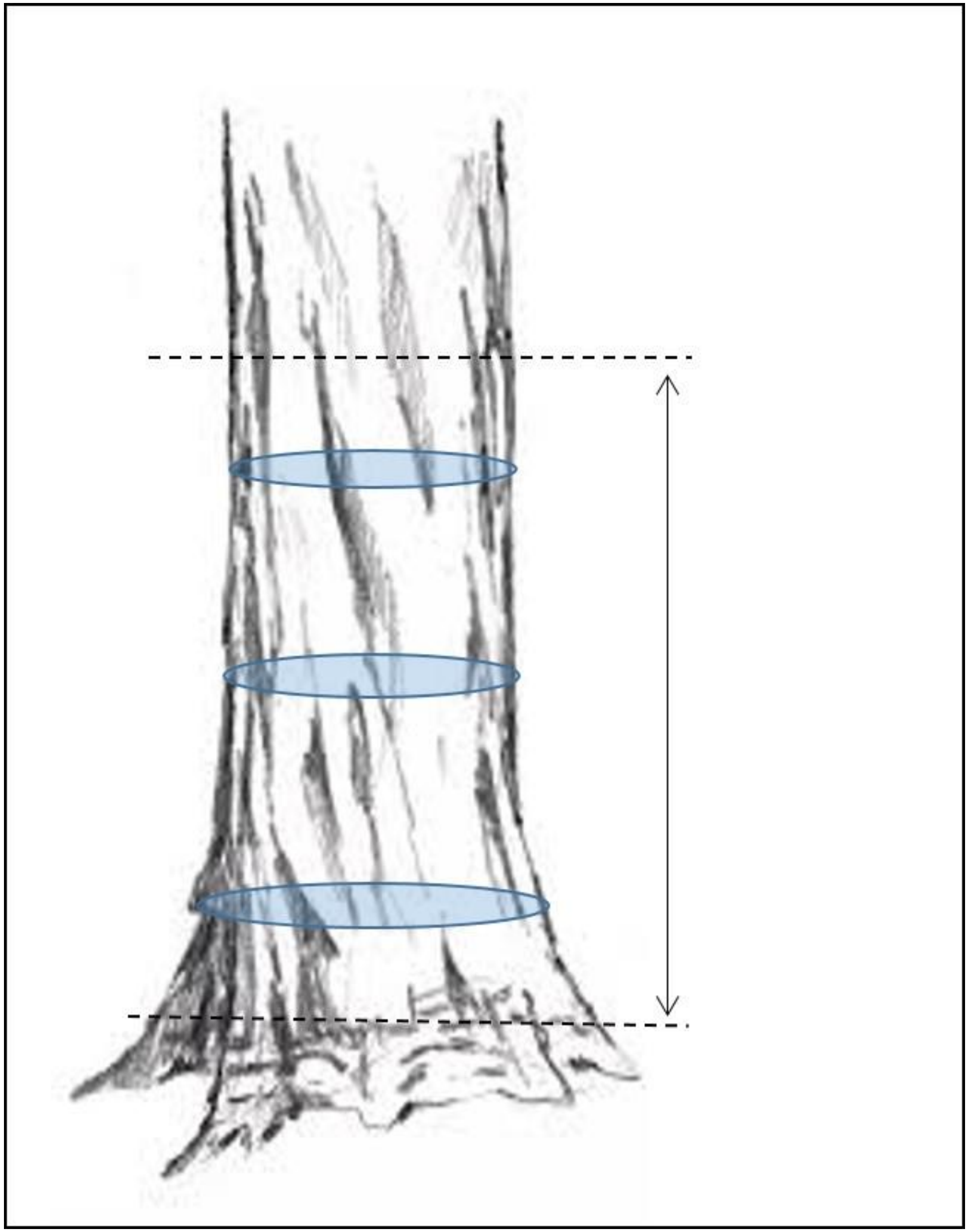


NO DECAY *INCIPIENT DECAY* *ACTIVE DECAY* *CAVITY*

	brown		non-brown	
AB	0.35	0.35	0.23	0.0
SM	0.32	0.32	0.25	0.0
YB	0.32	0.32	0.26	0.0

[C]
g/cm^3

Estimating C content of the Lower Bole



$$C_{bole} = V_{bole} * [C]$$

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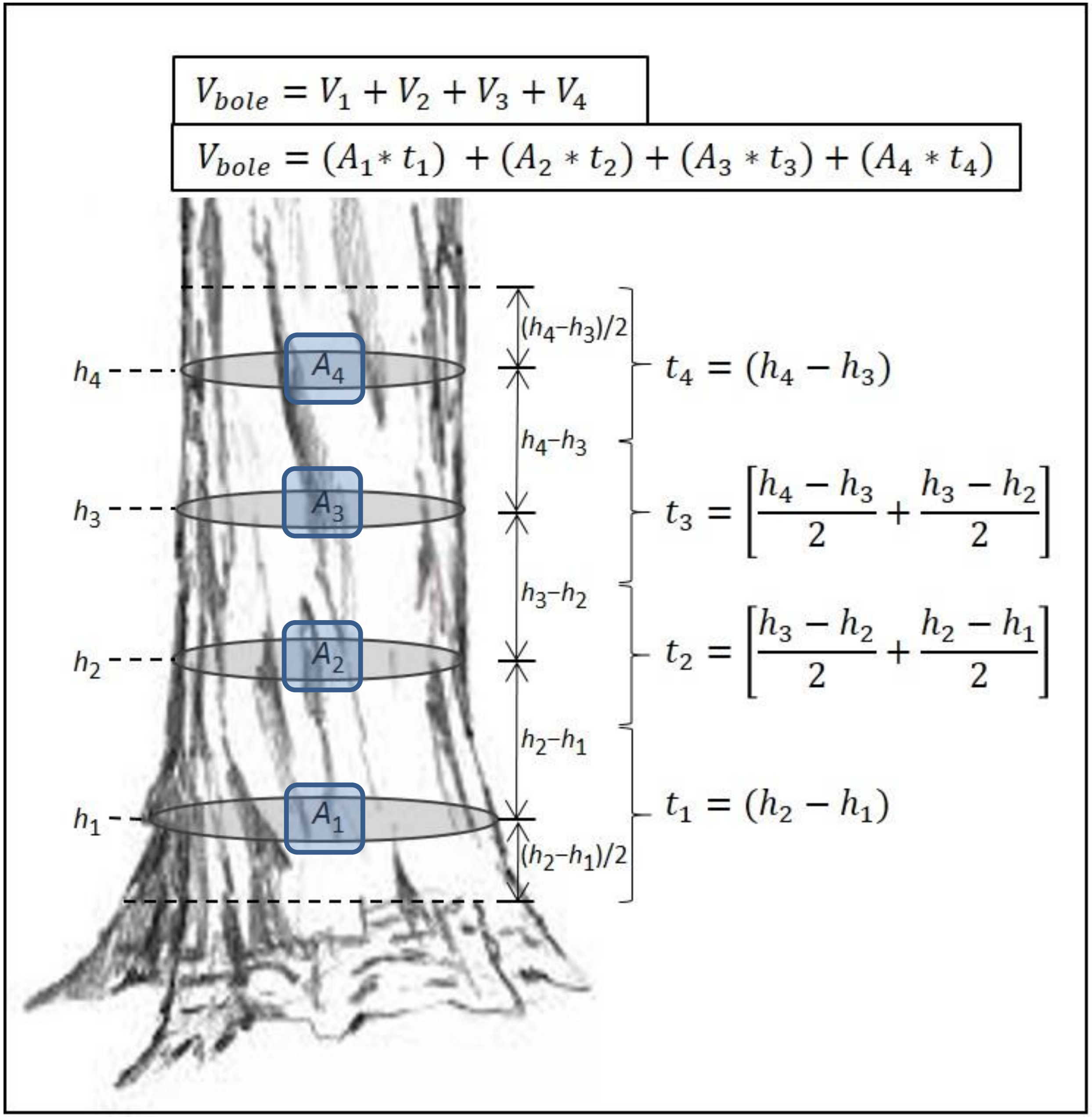
Estimating C content of the Lower Bole



$$V_{bole} = V_1 + V_2 + V_3 + V_4$$

$$V_{bole} = (A_1 * t_1) + (A_2 * t_2) + (A_3 * t_3) + (A_4 * t_4)$$

$$t_4 = (h_4 - h_3)$$

$$t_3 = \left[\frac{h_4 - h_3}{2} + \frac{h_3 - h_2}{2}\right]$$

$$t_2 = \left[\frac{h_3 - h_2}{2} + \frac{h_2 - h_1}{2}\right]$$

$$t_1 = (h_2 - h_1)$$

$$V_{bole} = \sum_{x=1}^{n} V_x$$

$$V_x = A_x * \ t_x$$

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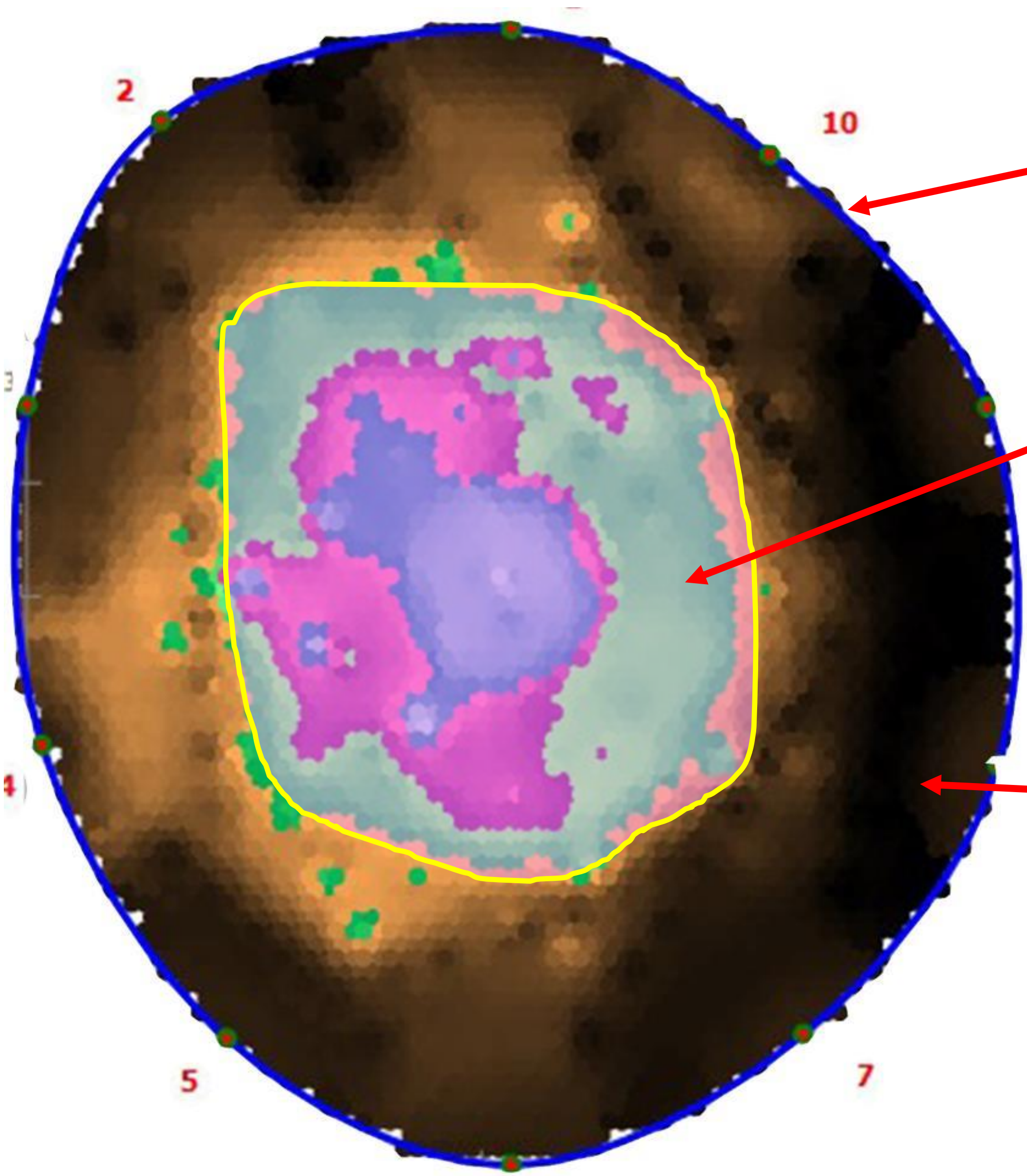


Area (cm^2)

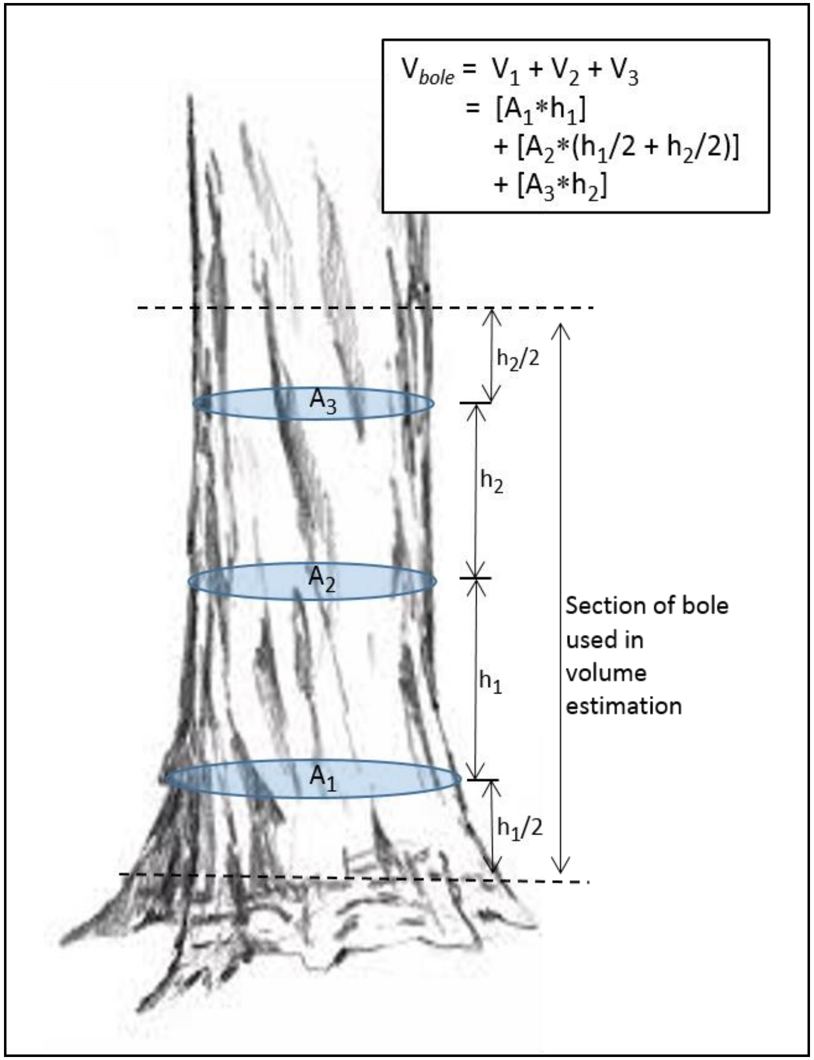
- inter-MP distances
- ImageJ (NIH)

% Non-brown

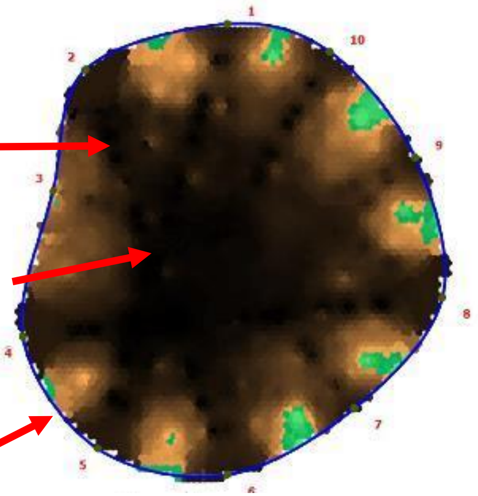
Software

% Brown

Estimating C content of the Lower Bole



$$\begin{aligned} V_{bole} &= V_1 + V_2 + V_3 \\ &= [A_1 * h_1] \\ &\quad + [A_2 * (h_1/2 + h_2/2)] \\ &\quad + [A_3 * h_2] \end{aligned}$$



100 % Brown

0 % Non-brown

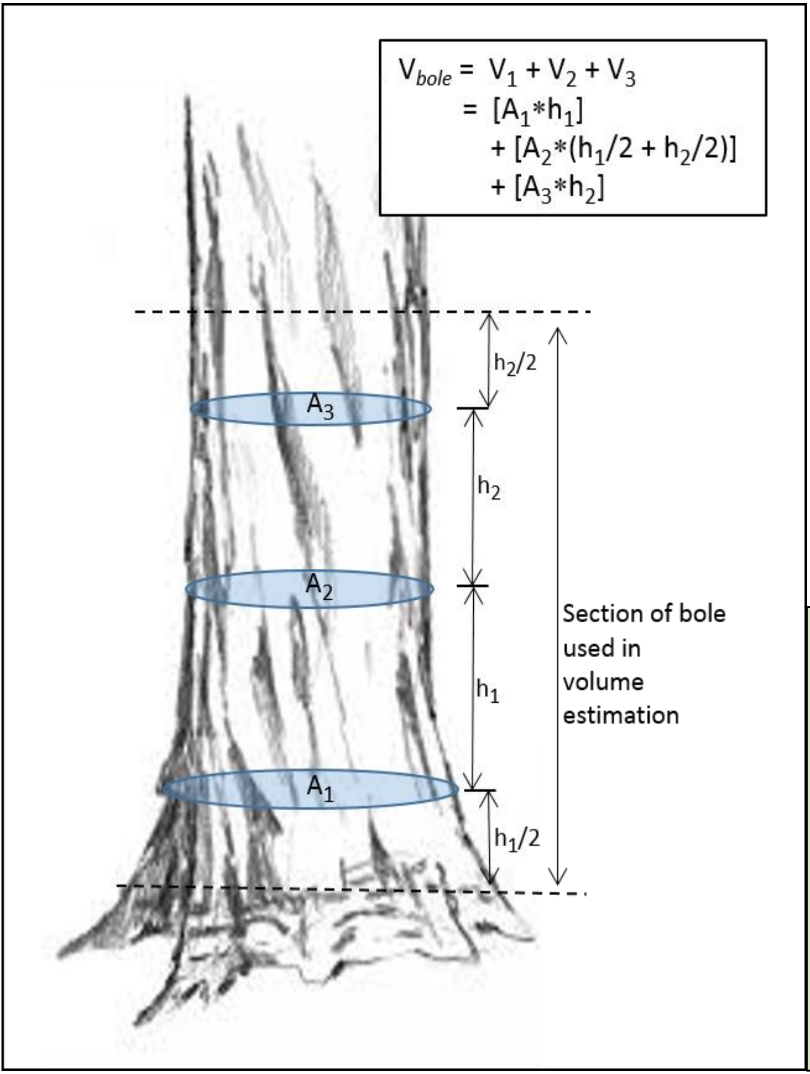
Area (cm^2)

Assuming no decay*:

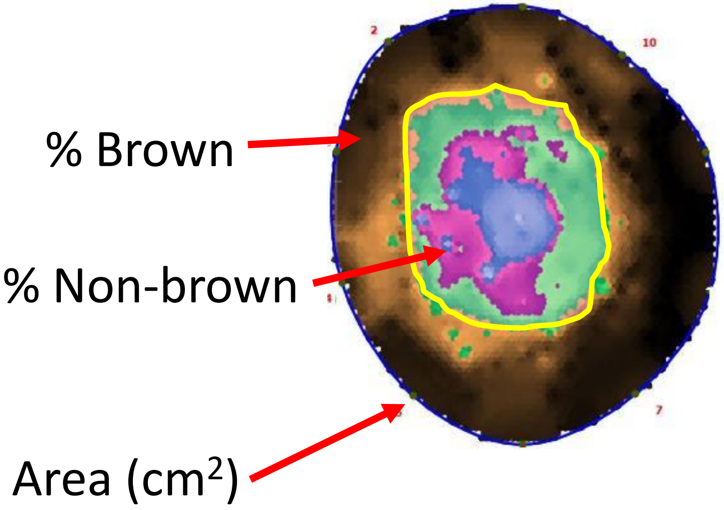
$$C_{ND} = V_{bole} * [C]_{br}$$

* (current C models)

Estimating C content of the Lower Bole



$$V_{bole} = V_1 + V_2 + V_3 = [A_1 * h_1] + [A_2 * (h_1/2 + h_2/2)] + [A_3 * h_2]$$



% Brown

% Non-brown

Area (cm^2)

Accounting for decay/cavity:

$$C_{tom} = (V_{br} * [\mathrm{C}]_{br}) + \begin{matrix} (V_{nbr} * [\mathrm{C}]_{nbr}) \\ \text{or} \\ (V_{nbr} * [\mathrm{C}]_{cav}) \end{matrix}$$

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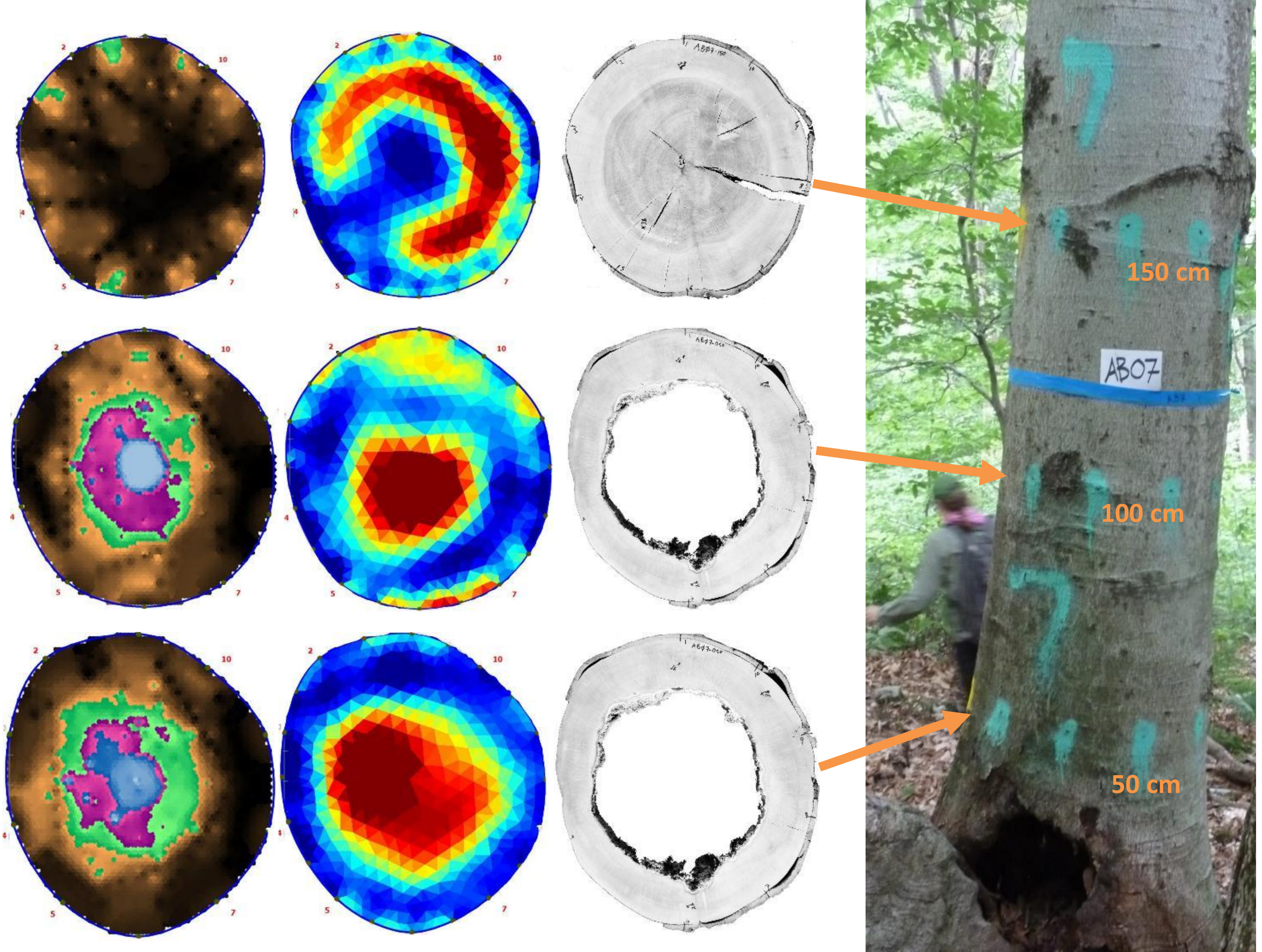
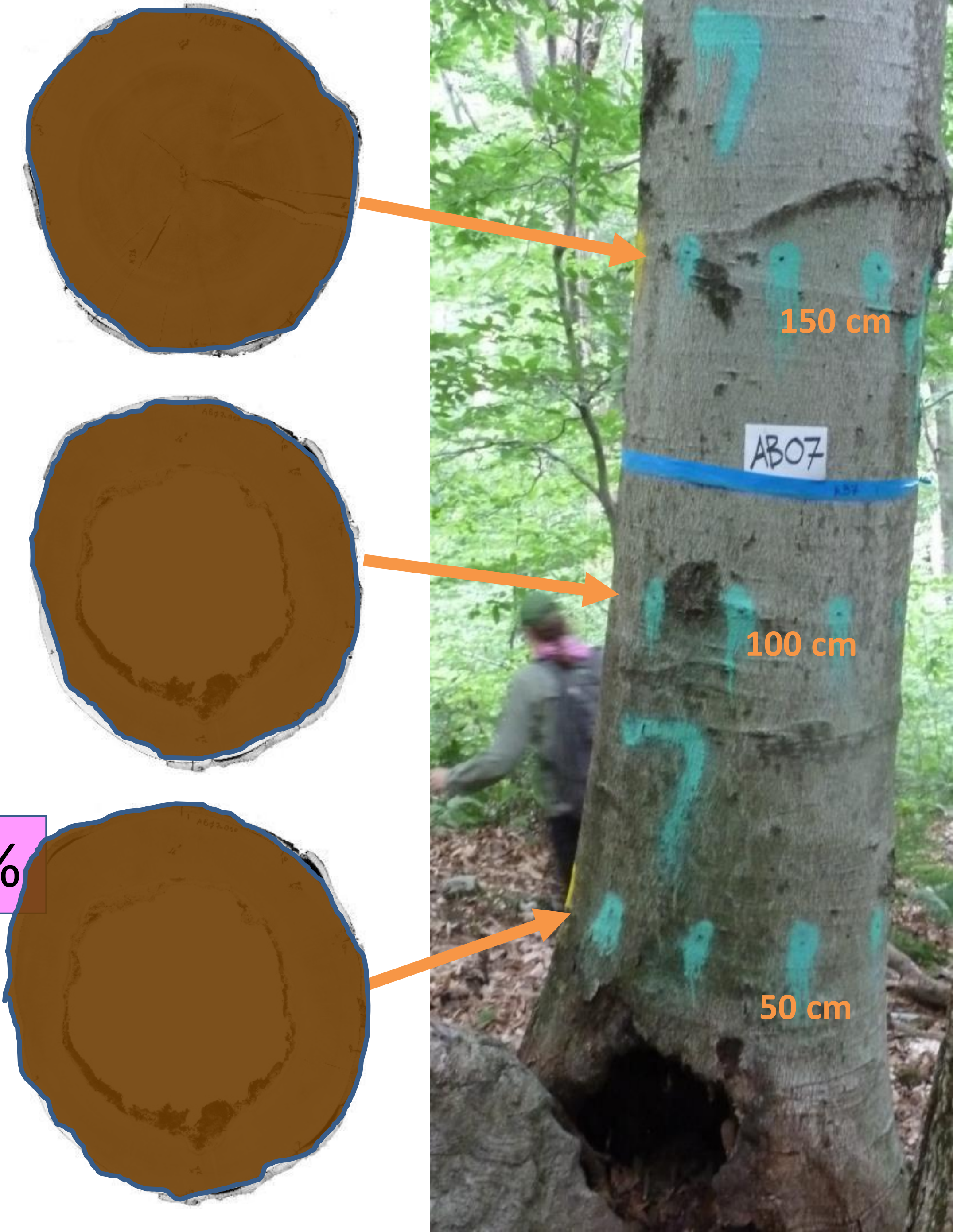

2
10
4
5
7
AB07-150
AB07-050
150 cm
100 cm
50 cm
AB07

	C (g)	
	NO DECAY	TOMOGRAPHY
150	30199	30199
100	34259	25351
50	38954	27268
	103412	82818

C overestimated by 19.9%



Estimating C content of the Lower Bole

	n	%C Overestimate in No Decay Model
American Beech	28	0 – 21.9
Sugar Maple	22	0.3 – 27.8
Yellow Birch	17	0 – 15.7

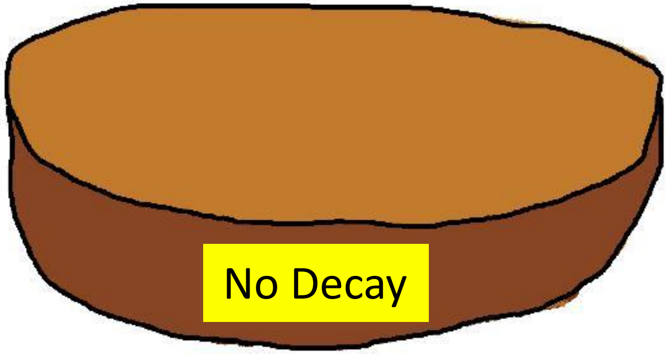
Validating Tomography-based Carbon Quantification

Indirect Estimate of C based on tomography

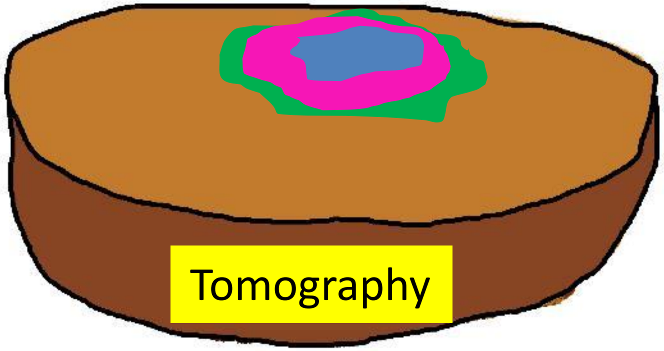
vs.

Direct Estimate of C based on mass

C_{ND}



C_{tom}



$$C_{mass} = \text{Mass (kg)} \times \%C$$

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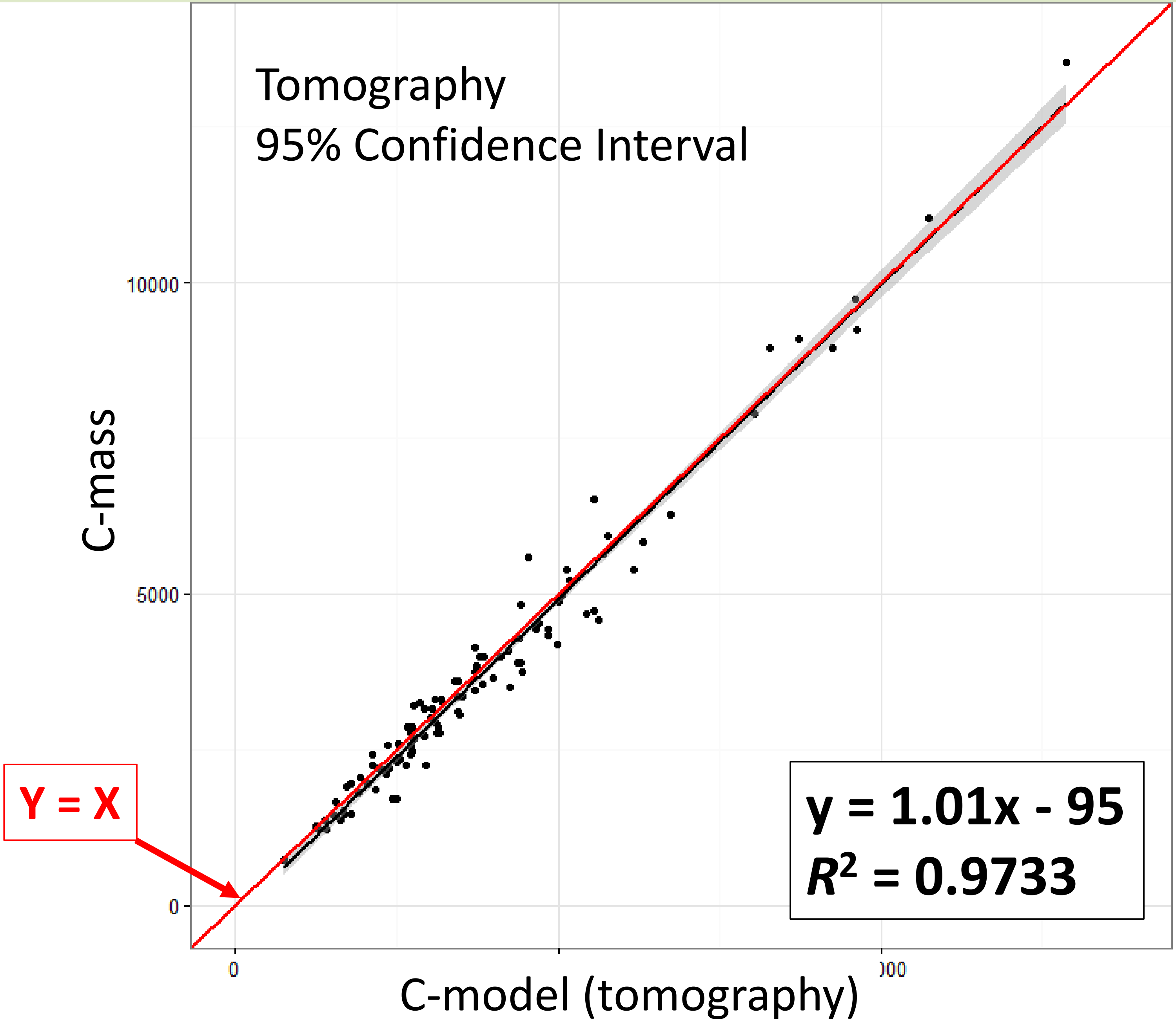
$$\widehat{V_{SD}} = A * \overline{t_{SD}}$$

Validating Tomography-based Carbon Quantification

n = 105

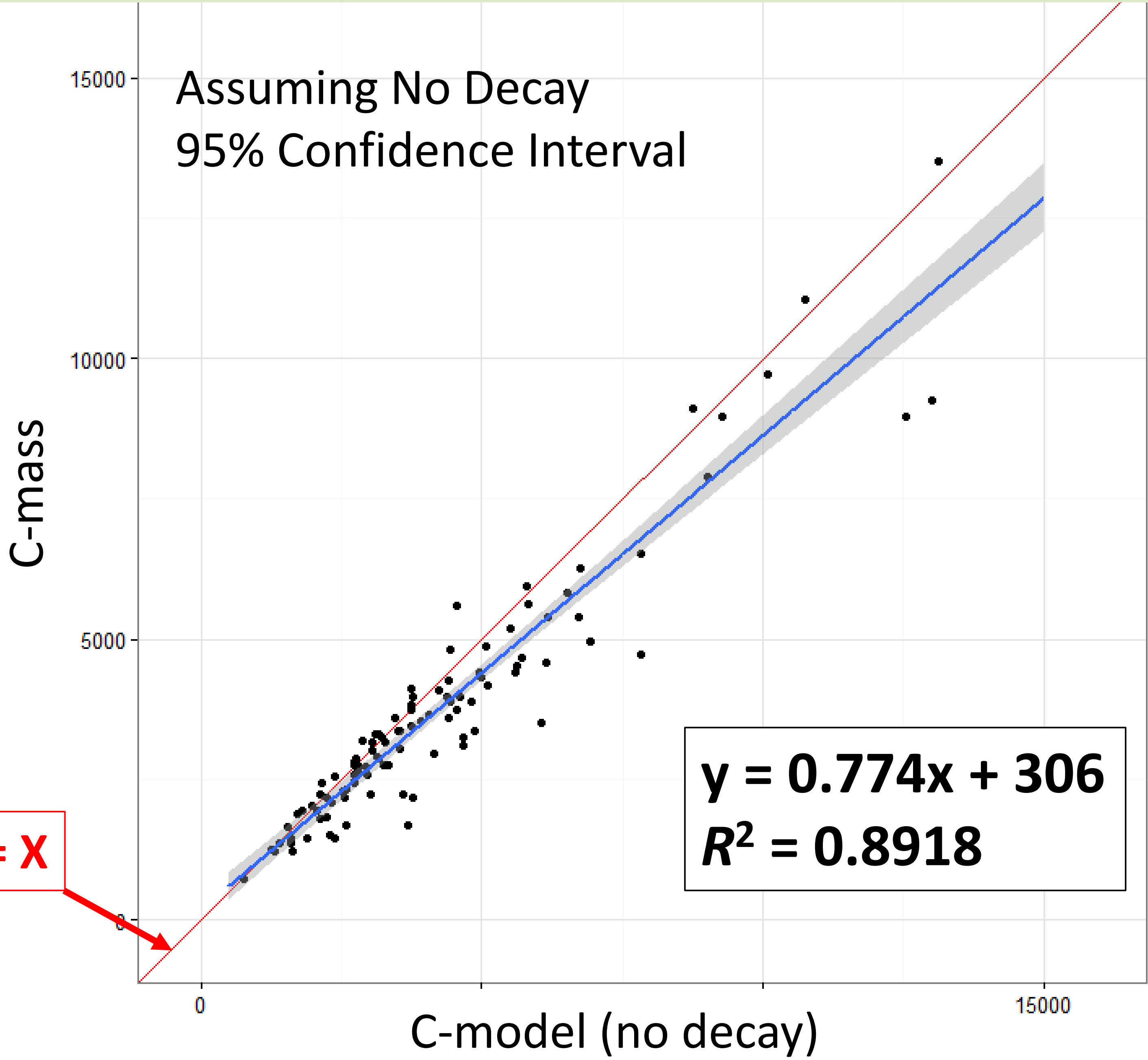


y = 1.01x - 95

R^2 = 0.9733

Validating Tomography-based Carbon Quantification

n = 105



Assuming No Decay

95% Confidence Interval

$y = 0.774x + 306$

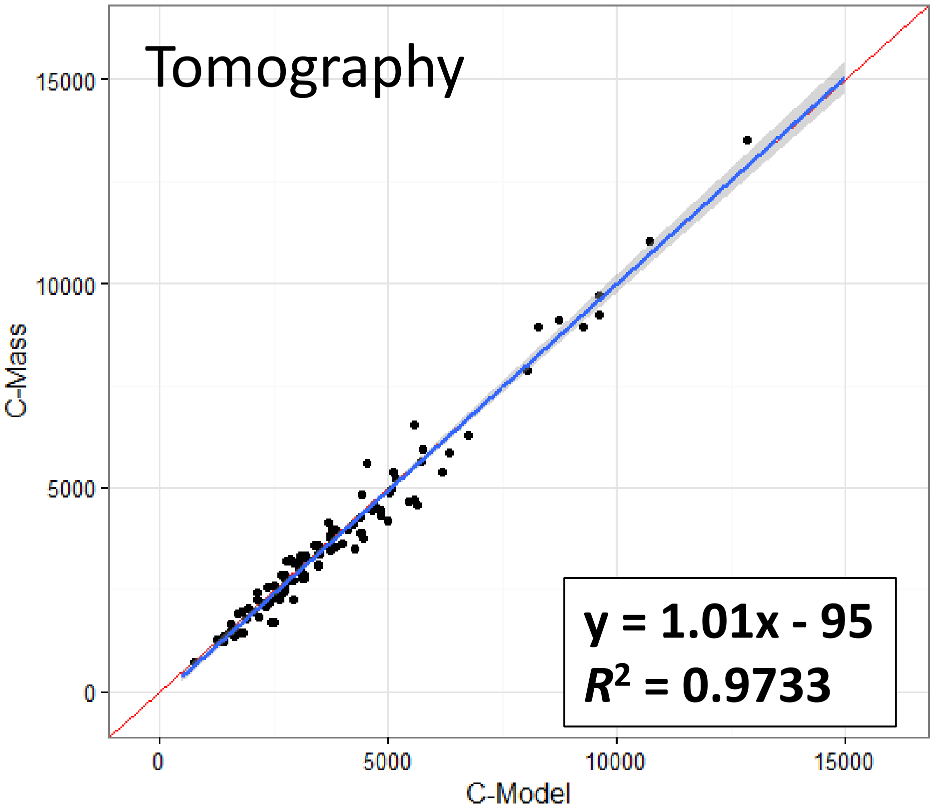
$R^2 = 0.8918$

Y = X

Validating Tomography-based Carbon Quantification

95% Confidence Intervals

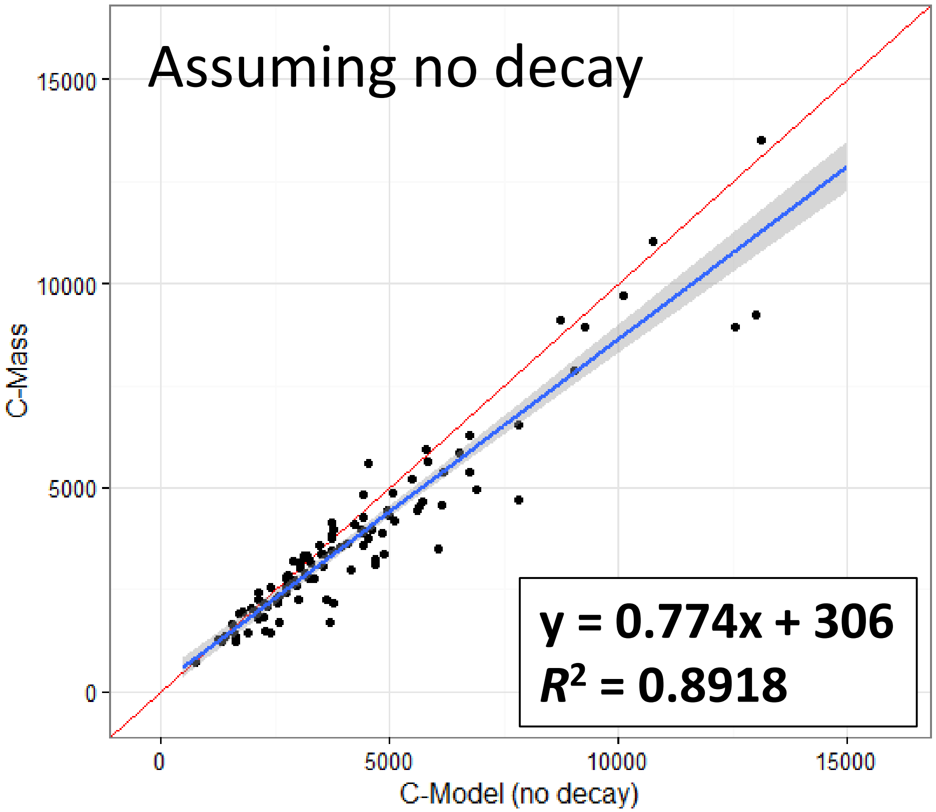
n = 105



Tomography

$y = 1.01x - 95$

$R^2 = 0.9733$



Assuming no decay

$y = 0.774x + 306$

$R^2 = 0.8918$

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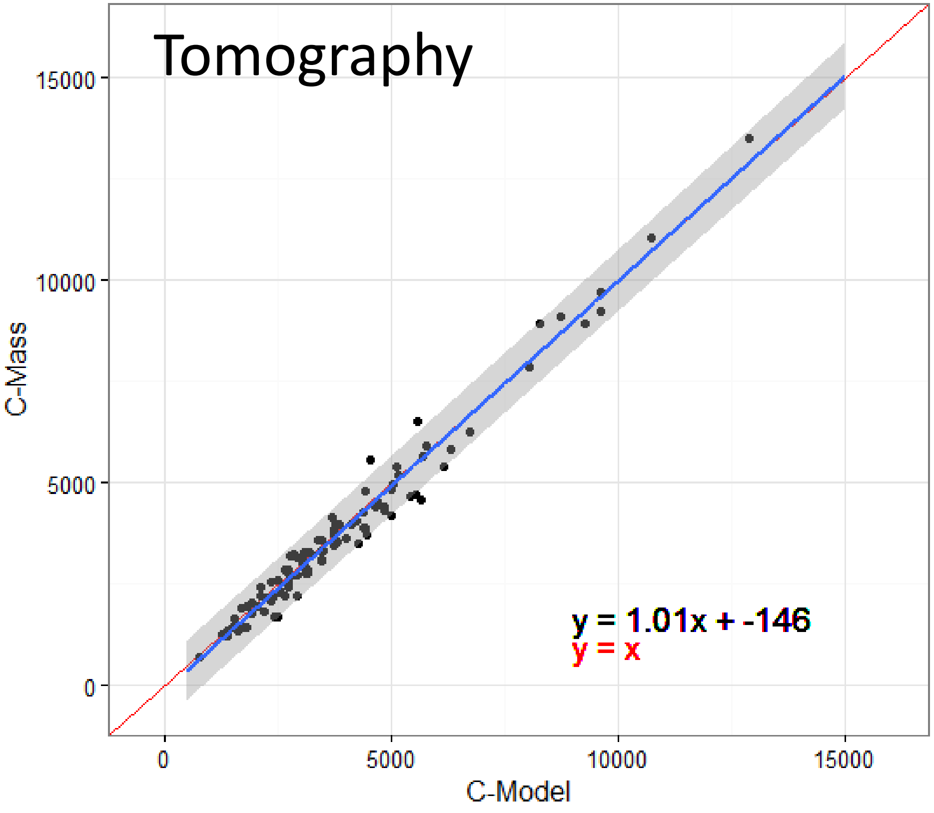
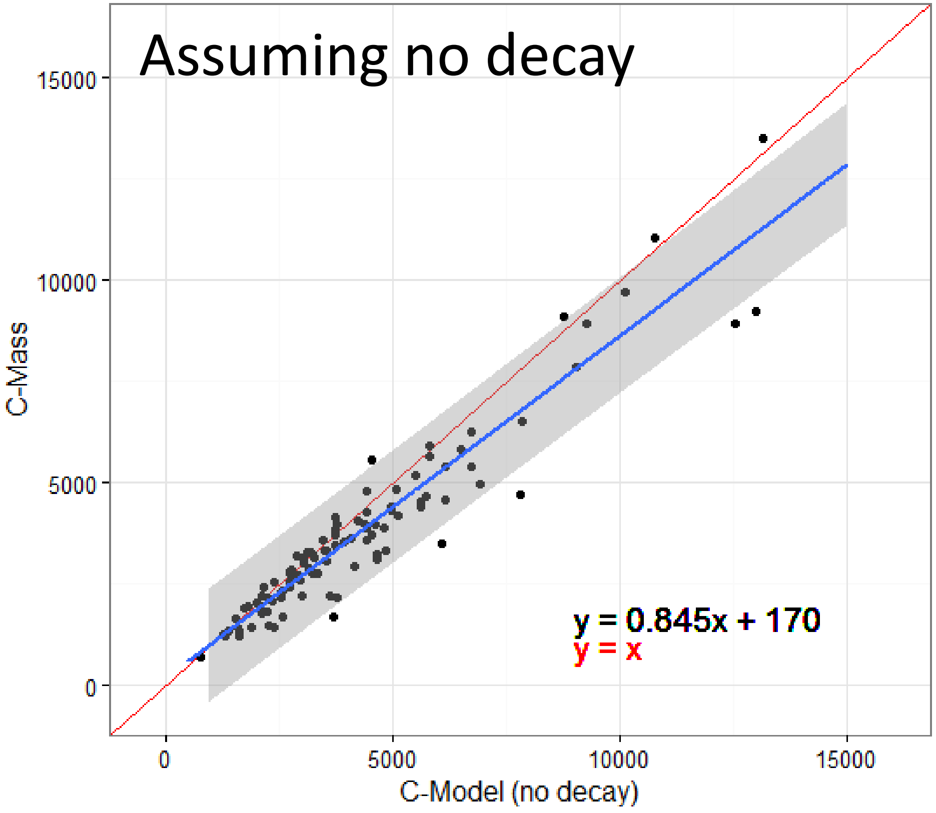
Validating Tomography-based Carbon Quantification

95% Prediction Intervals

n = 105





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Quantifying decay and carbon loss in trees

- Current C balance models overestimate the above-ground C pool in forests.
- Sonic and Electrical-Resistance Tomography:
  - Accurately predict the internal condition of living trees;
  - Facilitate a more accurate estimate of sequestered C;
  - Can be applied at larger scales to refine current C balance models.

Acknowledgments

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QUESTIONS?