Plant architecture phenotyping

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CIRAD

Partially inspired from presentations of M. Saudreau, et al.

Introduction

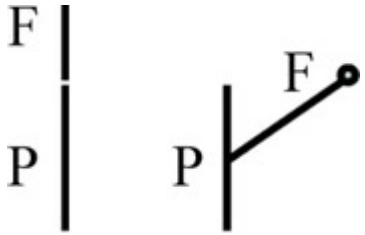
- Plant functioning highly depends on the spatial distribution of its organs
- As such, « 3D Plant Model » are interesting support to study the different processes ...
  - **Functional-Structural Plant Model** (FSPM)
- Access to parameters/information are usually difficult to obtain experimentally (root systems, 1 tree ~ 100 leaves; 1 field ~ 100 plants)
  - Need to adapt acquisition protocol

Introduction

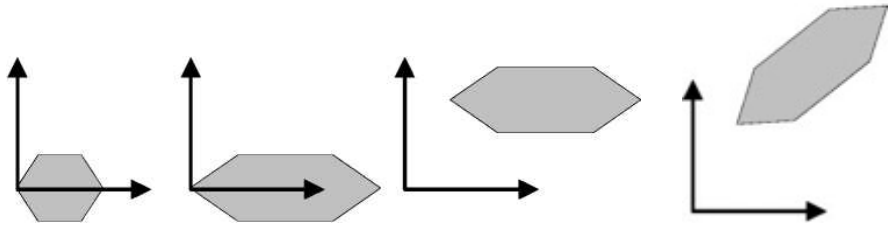
- Different **variables/architectural traits** with various interest ...

Typology - Entities

Topology - Connections



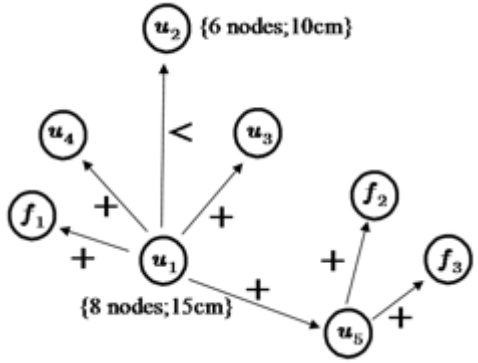
Geometry – Spatial distribution

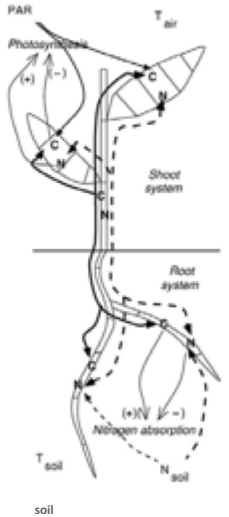


Introduction

- Different **variables/architectural traits** with various interest ...

Topology



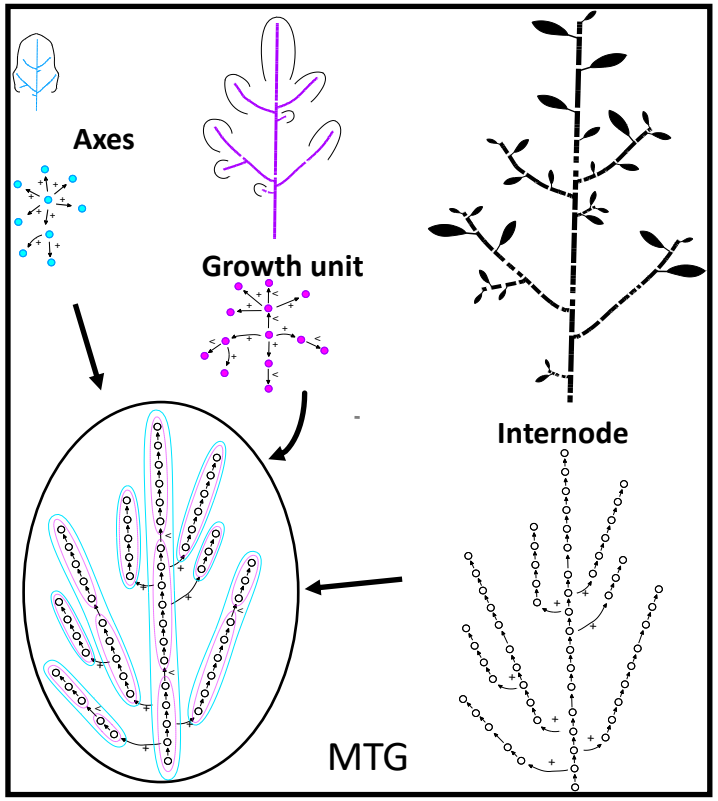


Geometry

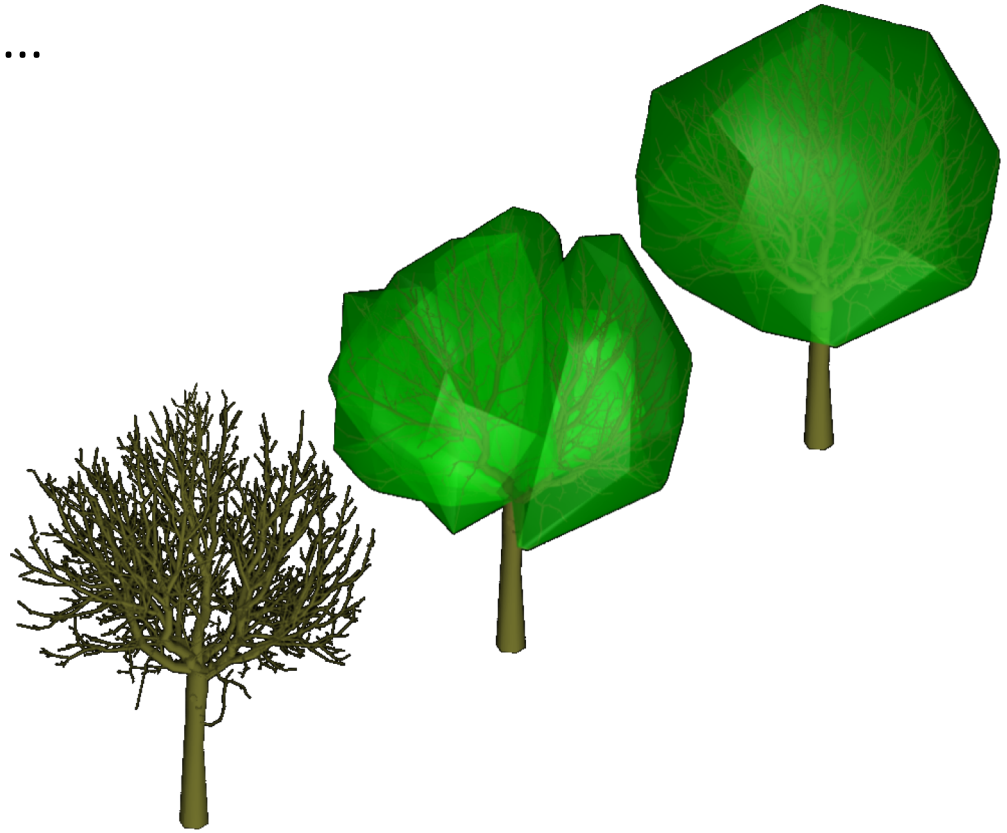
Rodriguez et al., 2011

Introduction

- Different **variables/architectural traits** with various interest ...



Topology

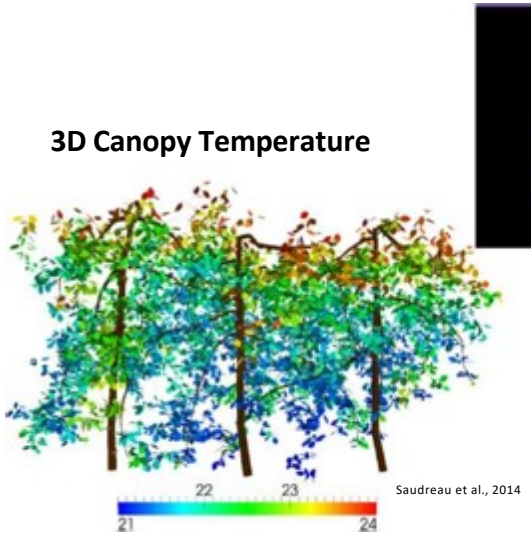


Geometry

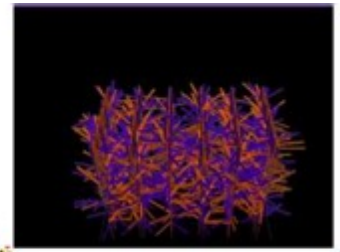
Introduction

- Multiples **processes/fonctions** ...

3D Canopy Temperature

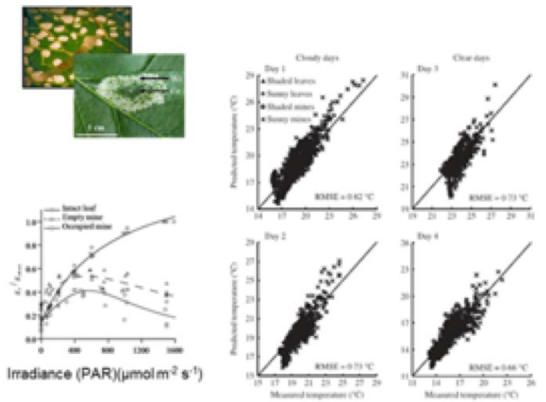


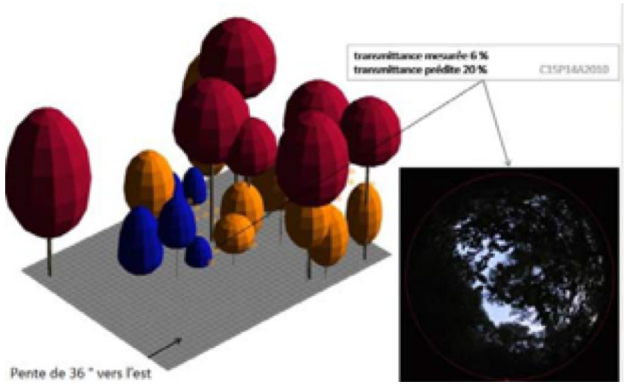
Saudreau et al., 2014



Vidal et al., 2015

Pathogen

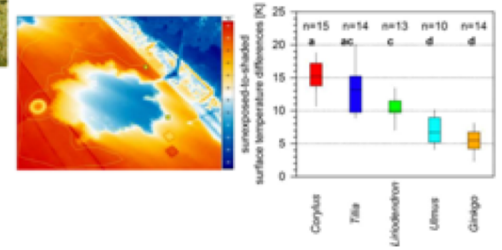




Shadowing

Agroforesterie

MicroClimat Urbain

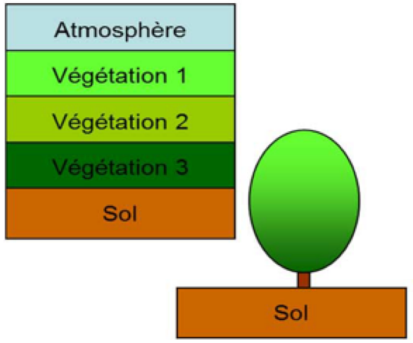


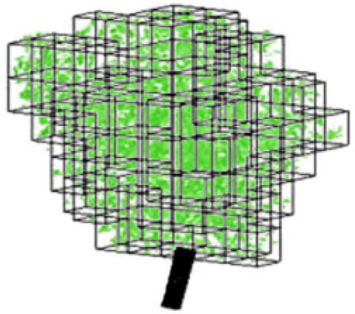
Introduction

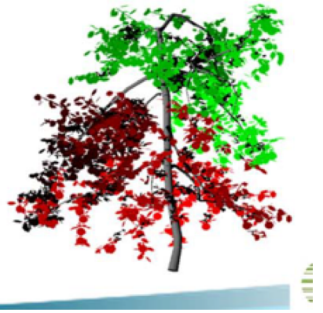
- Variable **degree of precision/details** ...

Spatial scale

Representation







- Finding the right balance between rapidity and level of precision

Introduction

- Two approaches of methodology of acquisition coexist:
  - With contacts

  - Contact free

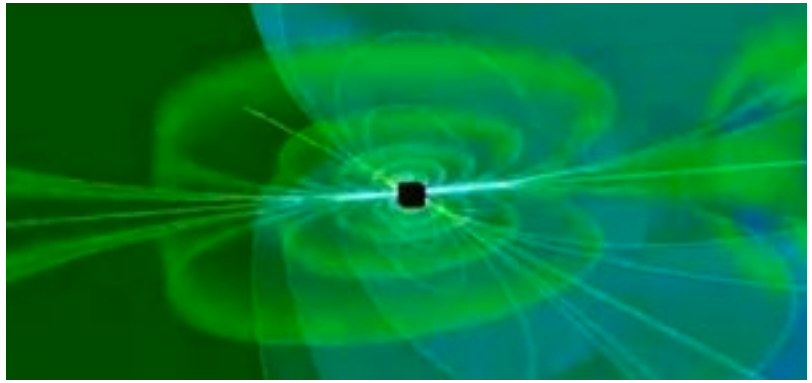
Contact methods

- Several «contact » methods have been developed ...

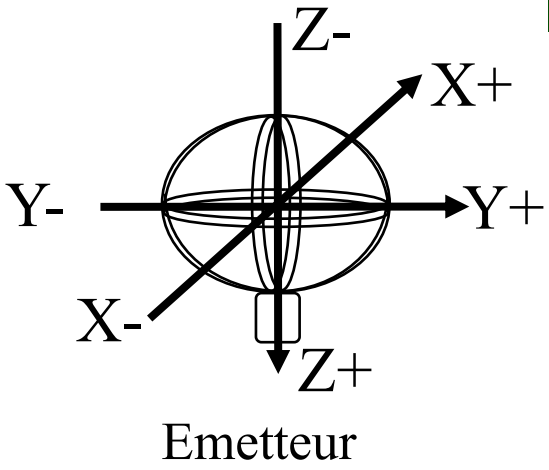
... But one was a reference for a long time

Contact methods

- Electro magnetic fields



polhemus fastrak

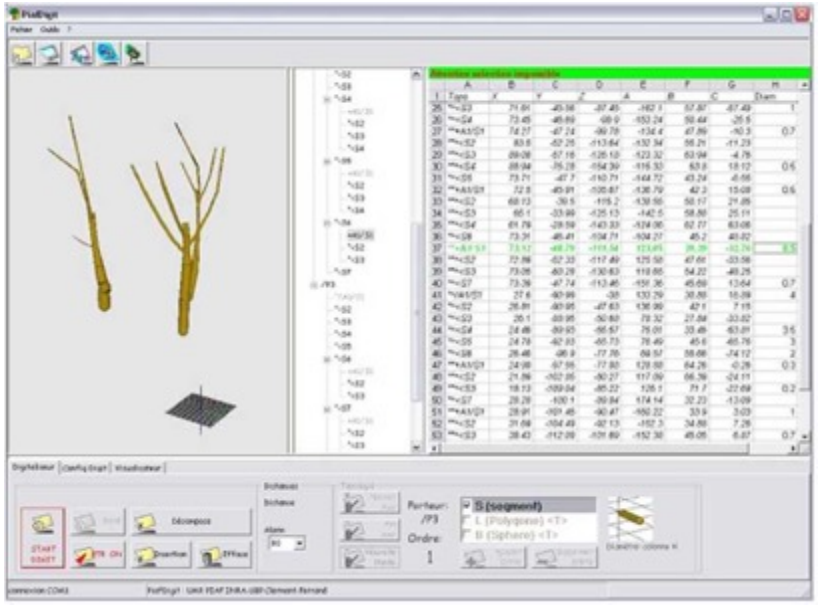


Emetteur

Contact methods

A flexible protocol of acquisition (Pol95, 3A, PiafDigit);

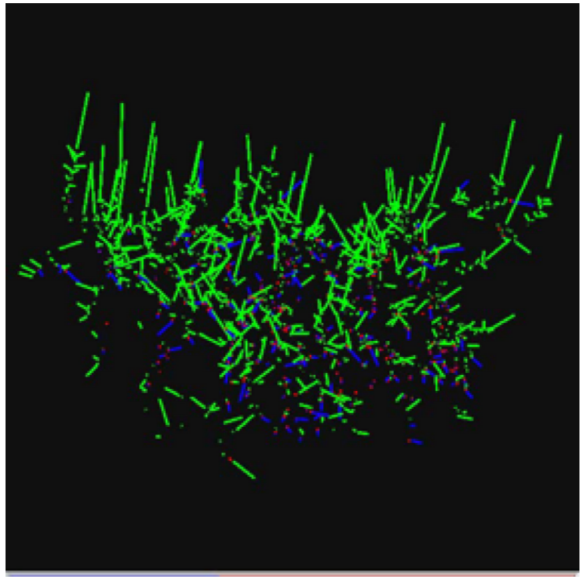
- Simultaneous acquisition:
  - Simplified topology
  - 3D Geometry
  - Additional information
- Configurable:
  - Entities and their attributes
  - Multi-scale topological relationships
- Ergonomics:
  - Topology verified in real time
  - Real-time 3D visualization



In contact with the plant, it is therefore possible to acquire additional information (type, colour, disease/insect, fruit, etc ...).

Contact methods

- Magnetic approach:
  - Semi-automatic : -
  - Comprehensive list of constituents : +
  - Nature of constituents : +
  - Encapsulate other parameters : +



Contact methods

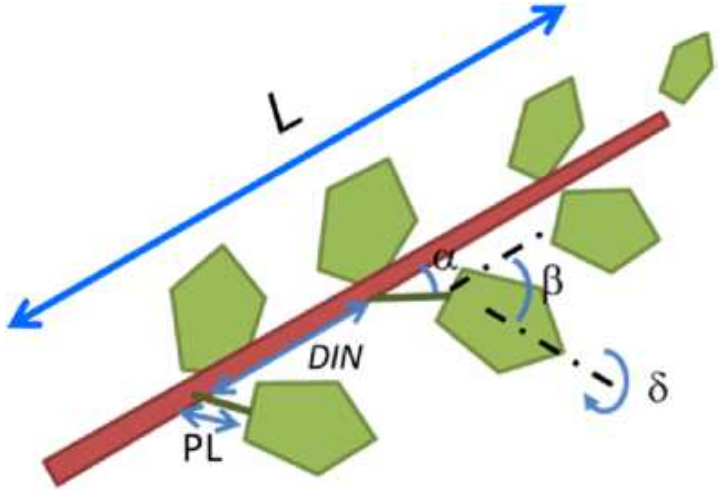
Magnetic digitizing (Pol95, 3A, PiafDigit)

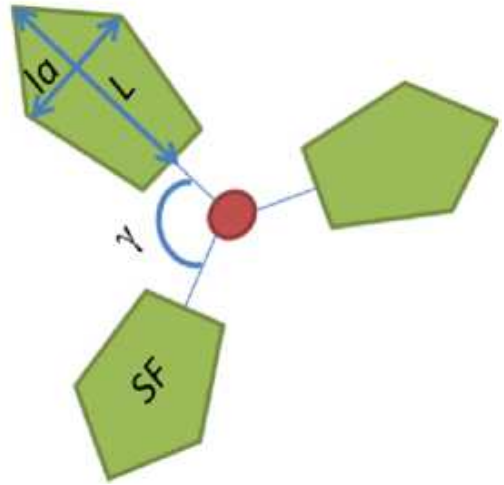
Reconstruction
of young walnut

- Comprehensive but time-consuming

Contact methods

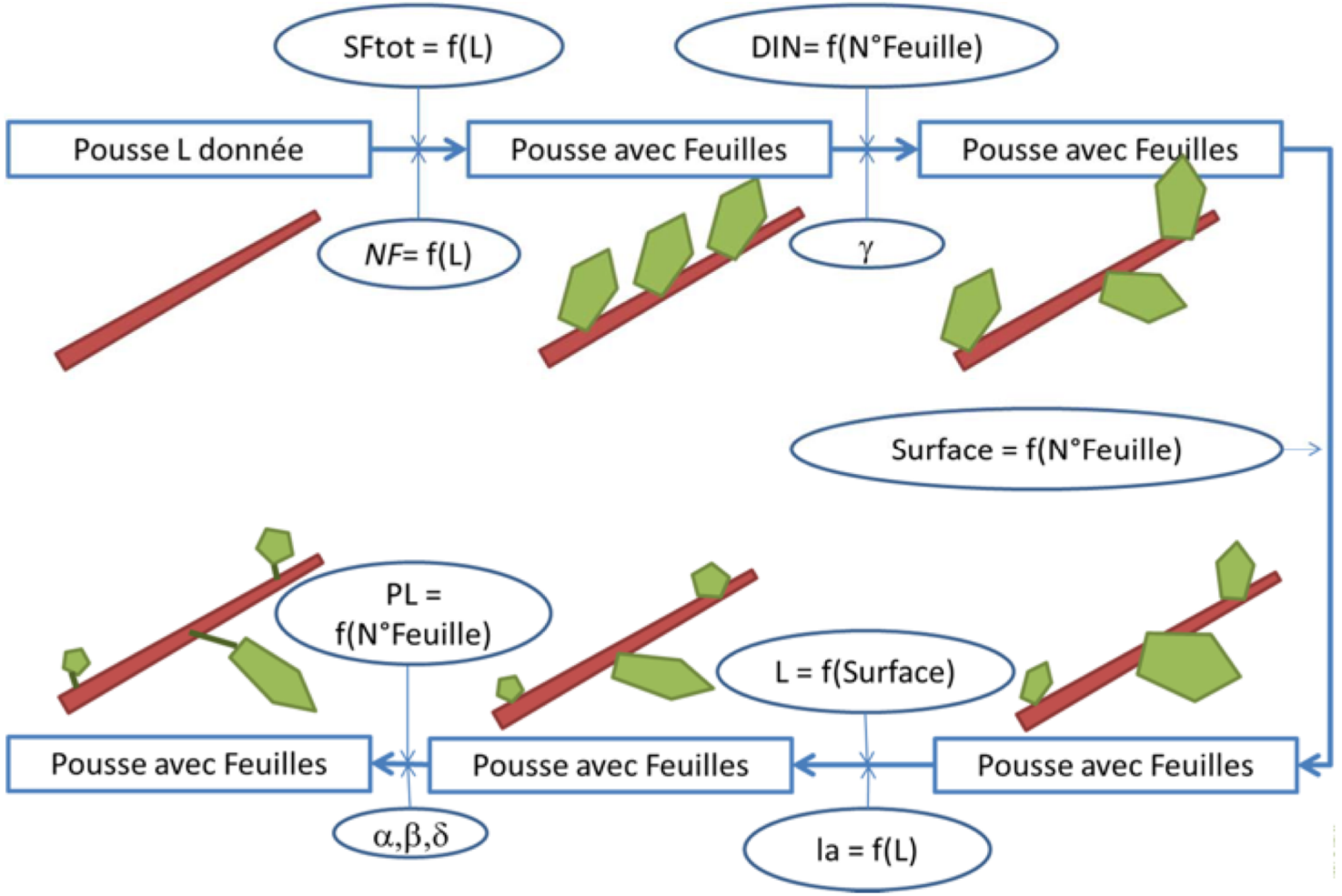
Lighten digitizing to estimate leaf area by using **allometric relations** at shoot scale





Contact methods

Lighten digitizing to estimate leaf area by using **allometric relations** at shoot scale



Contact methods

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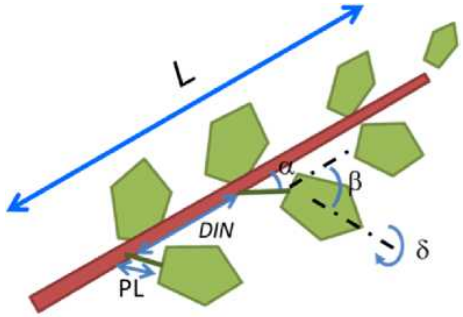
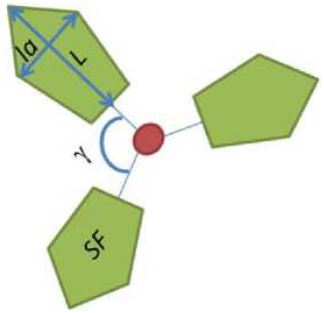
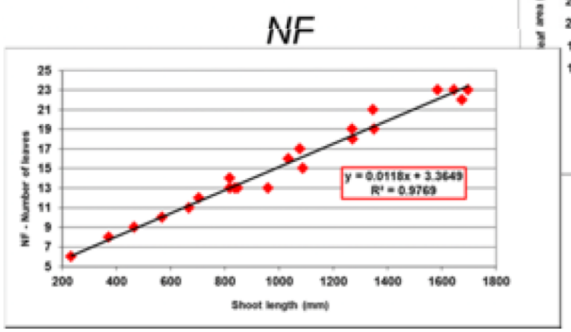
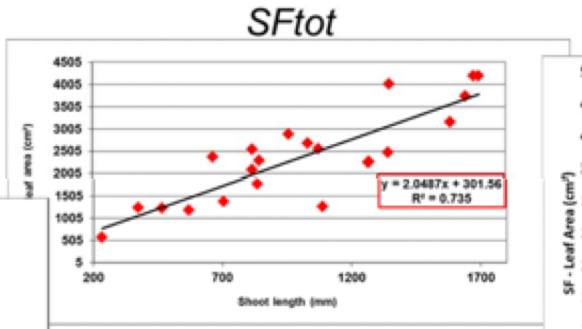
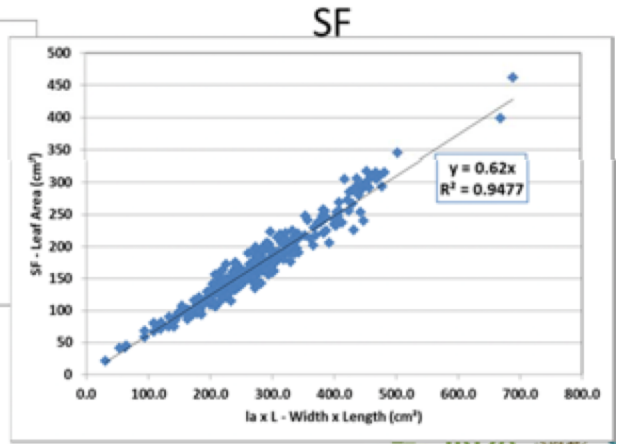




Lime tree

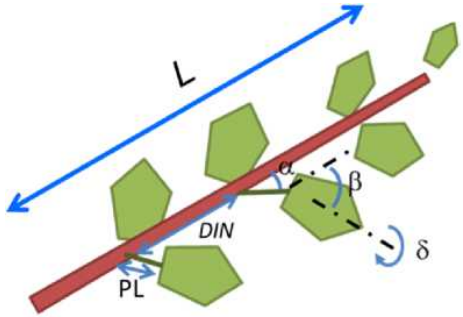


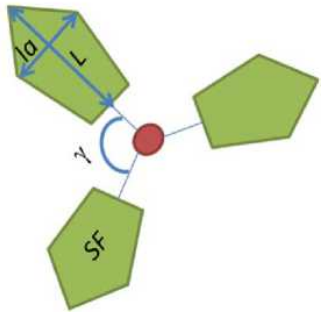




Contact methods

Lighten digitizing to estimate leaf area by using **allometric relations** at shoot scale

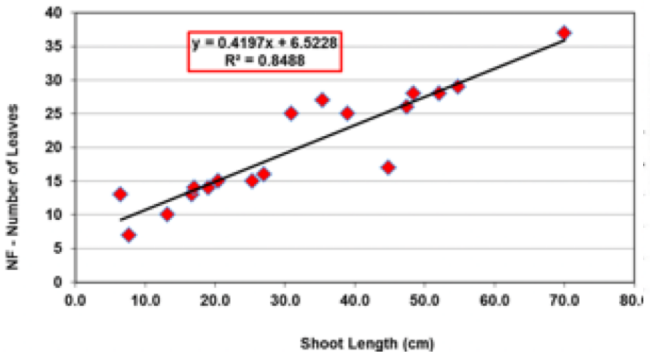




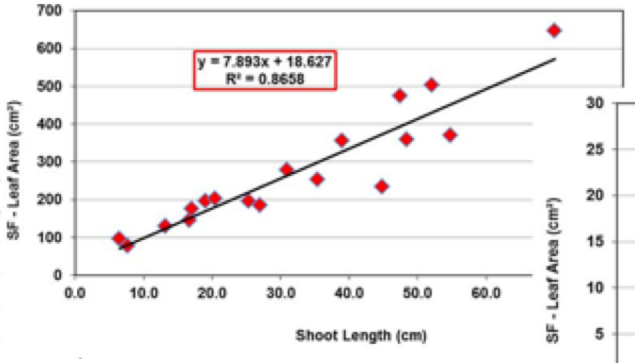
Apple tree

(cv. Pichounette)

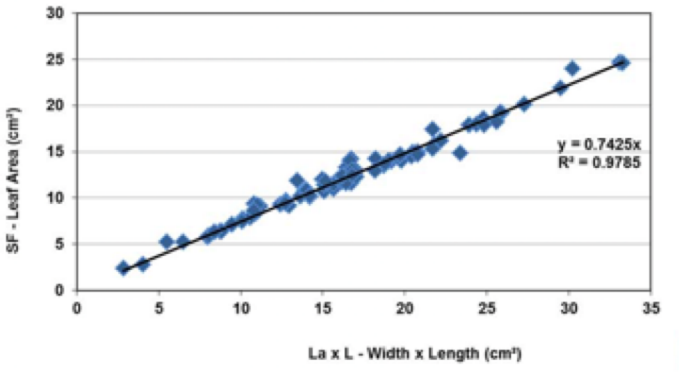
NF



SFtot



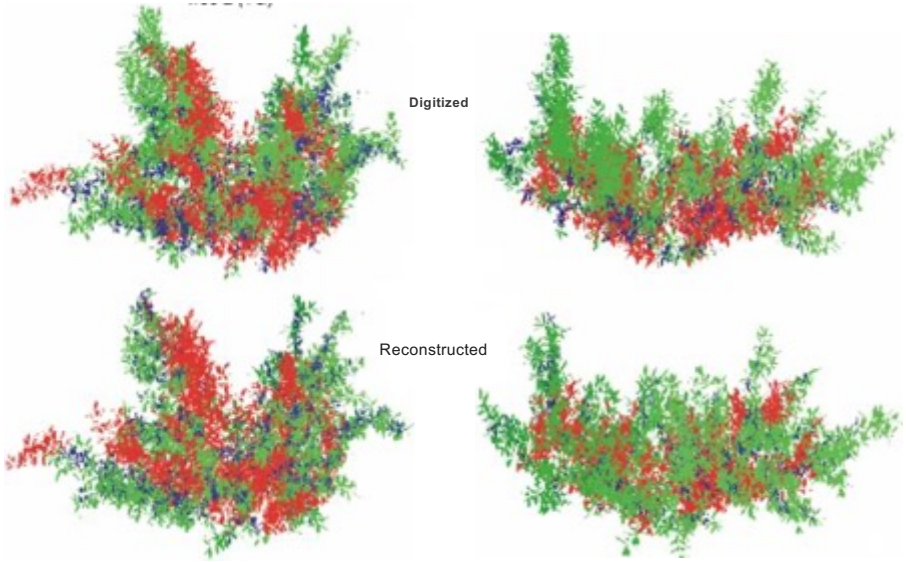
SF

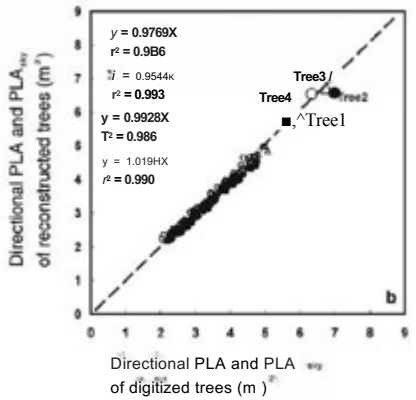


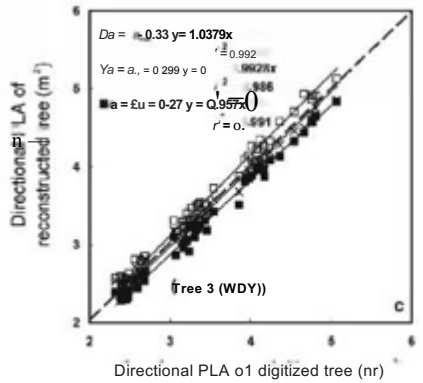
Contact methods

Lighten digitizing to estimate leaf area by using **allometric relations** at shoot scale

Pêchers (sonohat *et al.*, 2006)





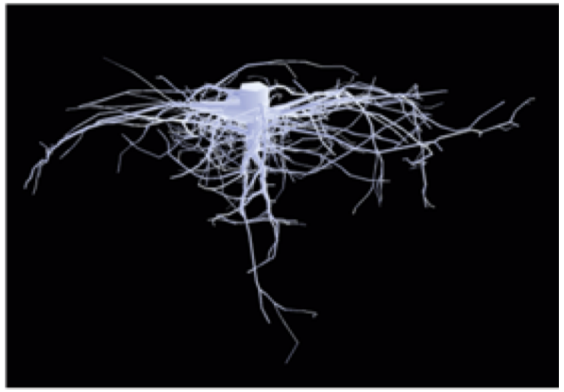


Small walnut

Contact method

Real plants vs. Digitized plants

Small mango tree

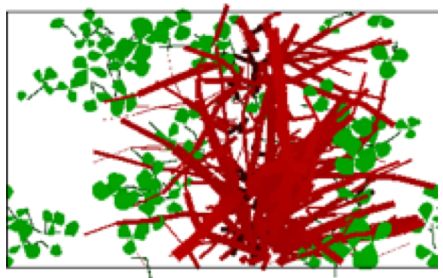


Root system

Mature walnut (8 m)

A reference method for plant of reasonnable size.

Walnut



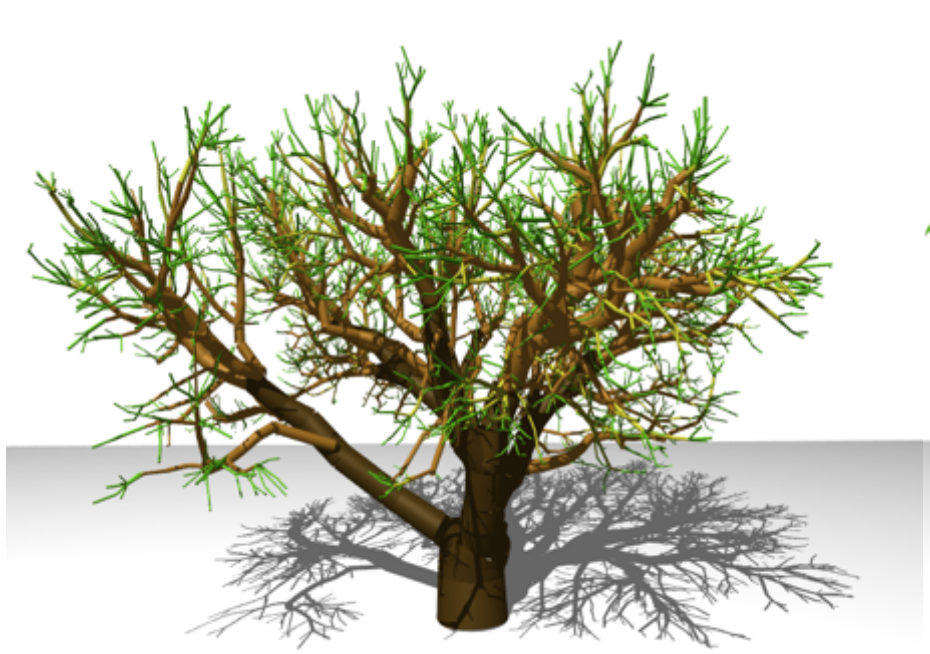
Clover / Fetuque Mixture

Measuring Architecture

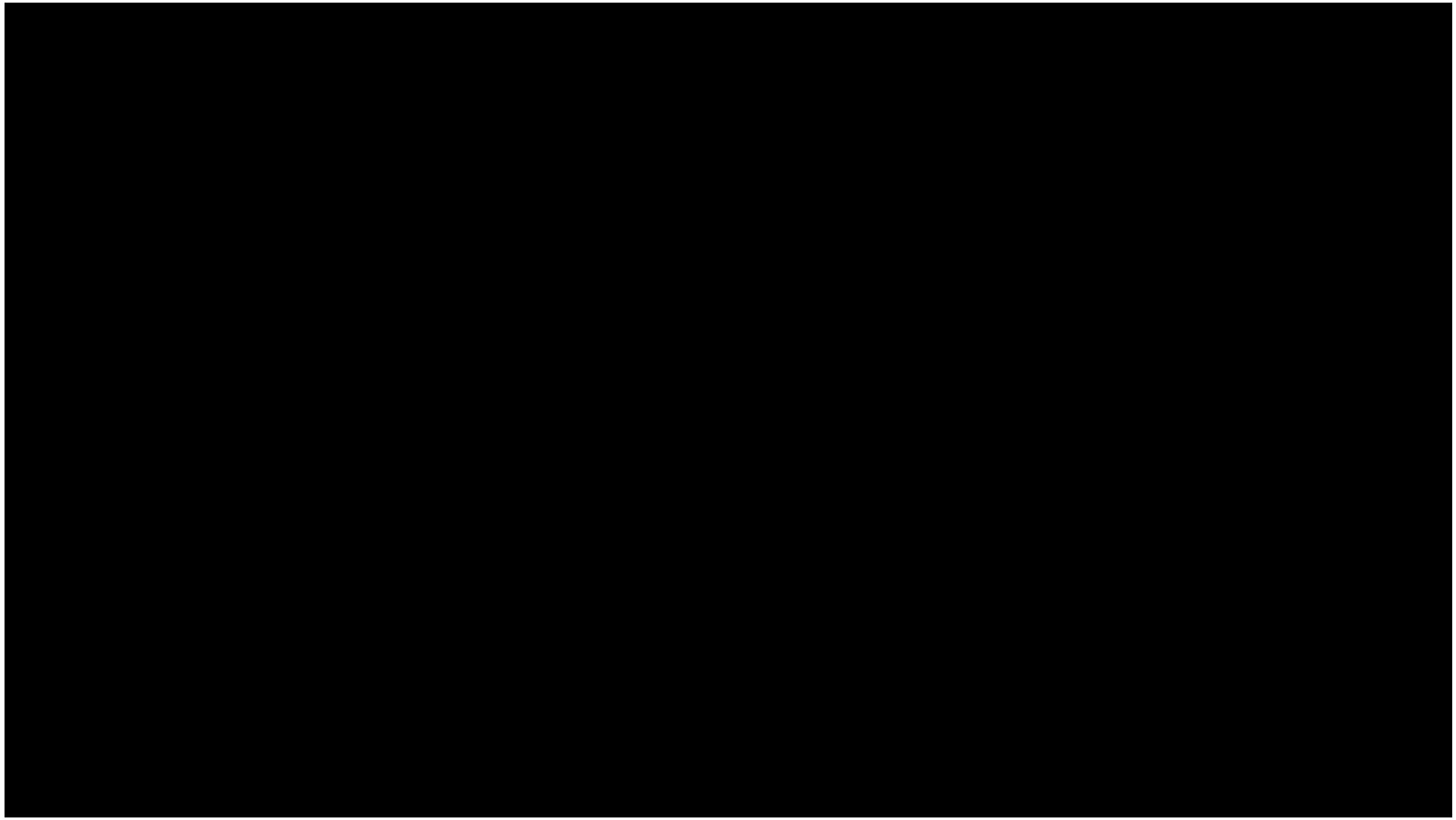
- One 13-years-old mango tree
  - For every growth unit:
    - Its top coordinates,
    - Its diameter,
    - Its type (Old, Recent),
    - The number of leaves,
    - …
  - Around 15000 clicks for approx. 8000 growth units

➢ Measured in 1 month.

Results



Results



Participation of A. Marquier, I. Grechi, S. Persello, C. Soria and F. Normand

Contact methods

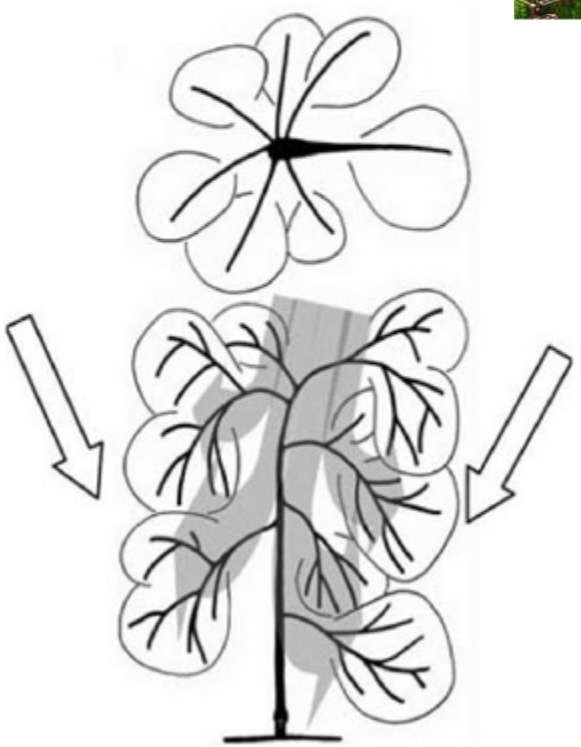
Some applications

Centrifugal Yield

Comparison architecture / shoots

Witness Yield

Centrifugal Yield



Architecture more « efficient » in terms of intercepted light ?

Willaume et al., 2004, Trees

Contact methods

Some applications

Comparison architecture / shoots

Witness Yield

Centrifugal Yield

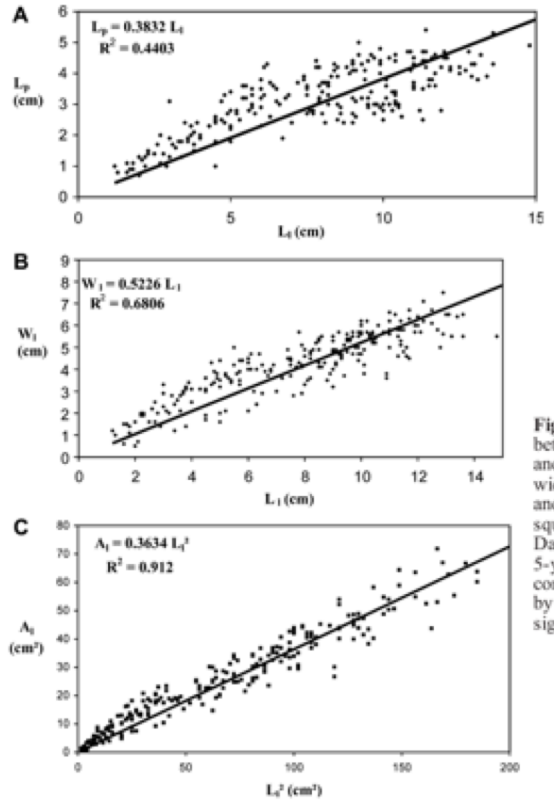


Fig. 2 Allometric relationships between **a** petiole length, L_p, and lamina length, L_l, **b** lamina width, W_l, and lamina length, L_l, and **c** leaf area, A_l, and the square of lamina length, L_l^2. Data collected on 230 leaves of 5-year-old "Galaxy" trees. All correlations were best adjusted by linear regressions and were significant at $P<0.05$

Measurement of allometric relationships

Willaume et al., 2004, Trees

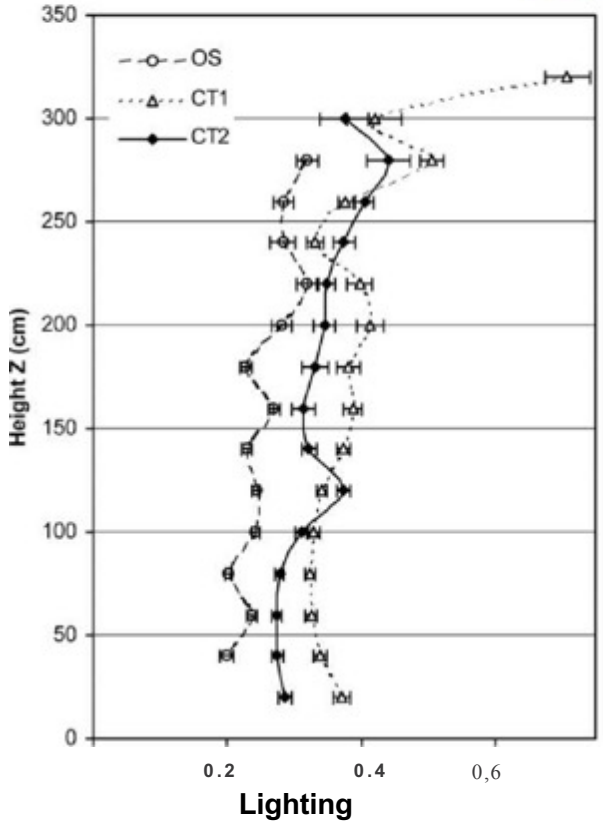
Contact methods

Some applications ...

Comparison architecture / shoots

Witness Yield

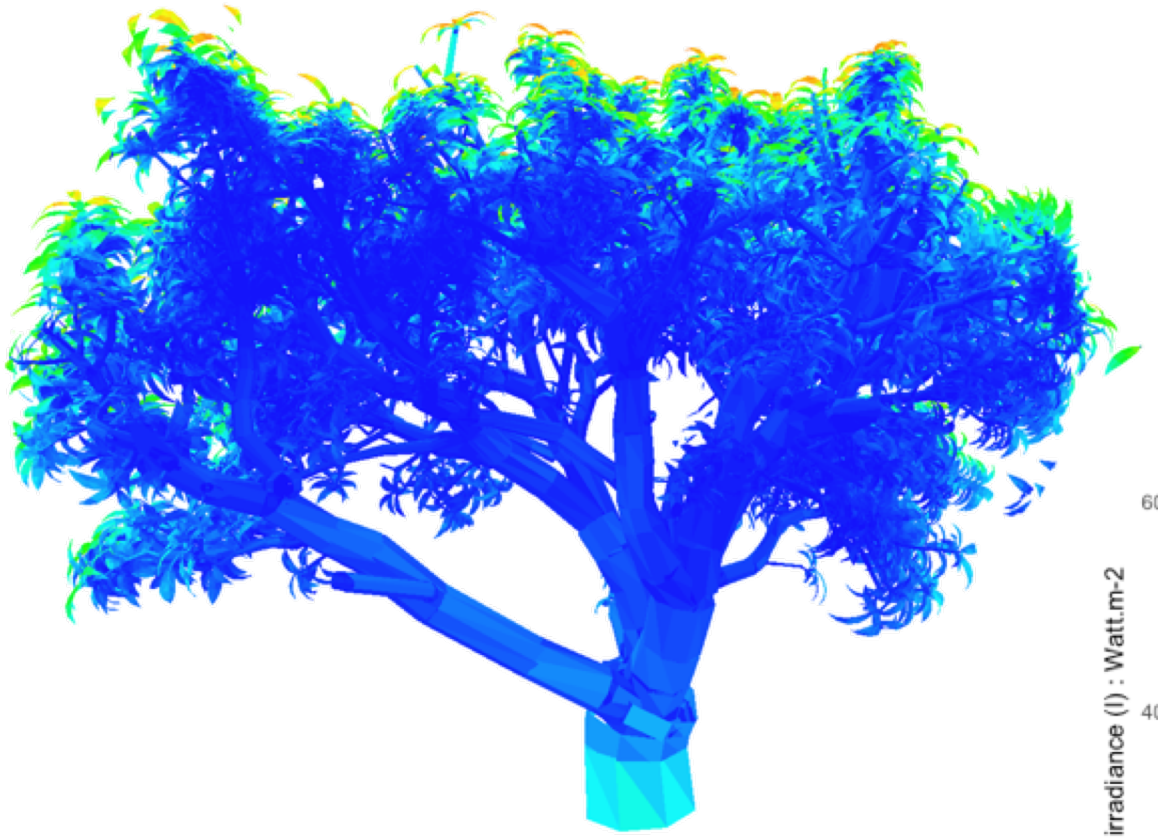
Centrifugal Yield

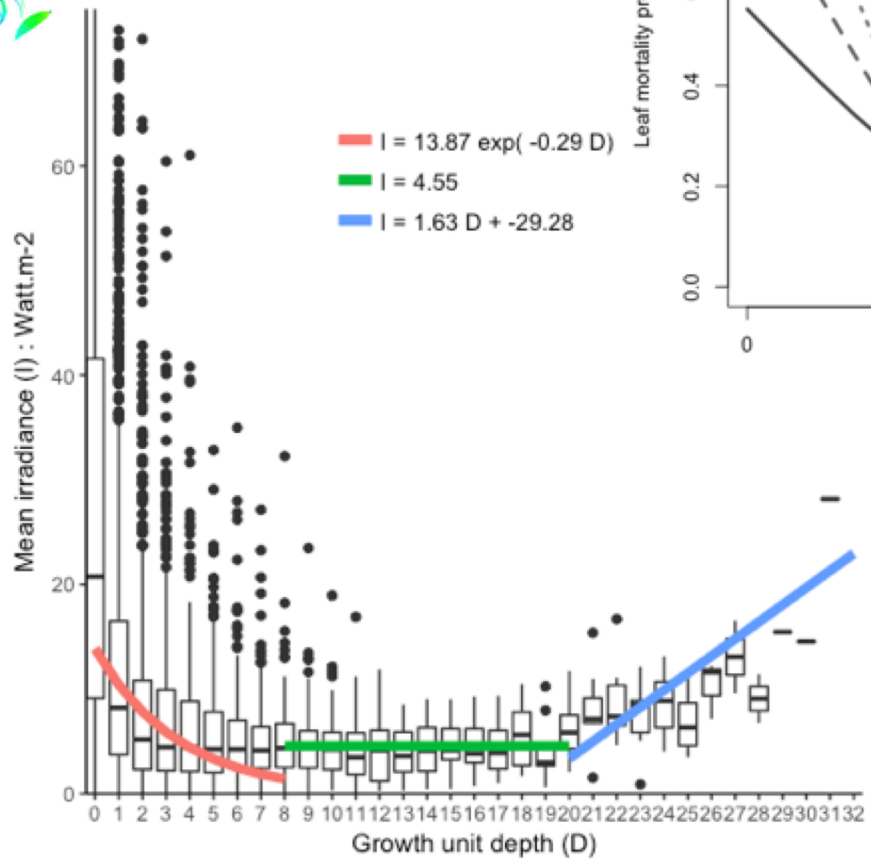


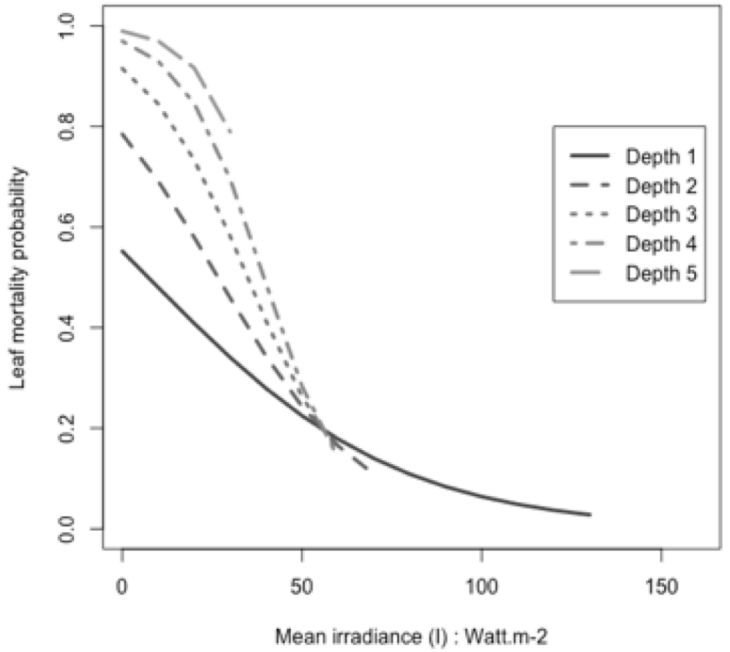
Comparison of intercepted light at different layers

Willaume et al., 2004, Trees

Light interception and leaf mortality on mango trees





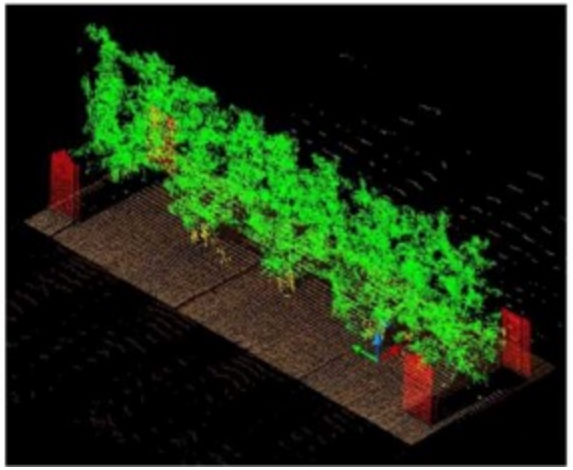


(Boudon et al., 2018)

Contactless method

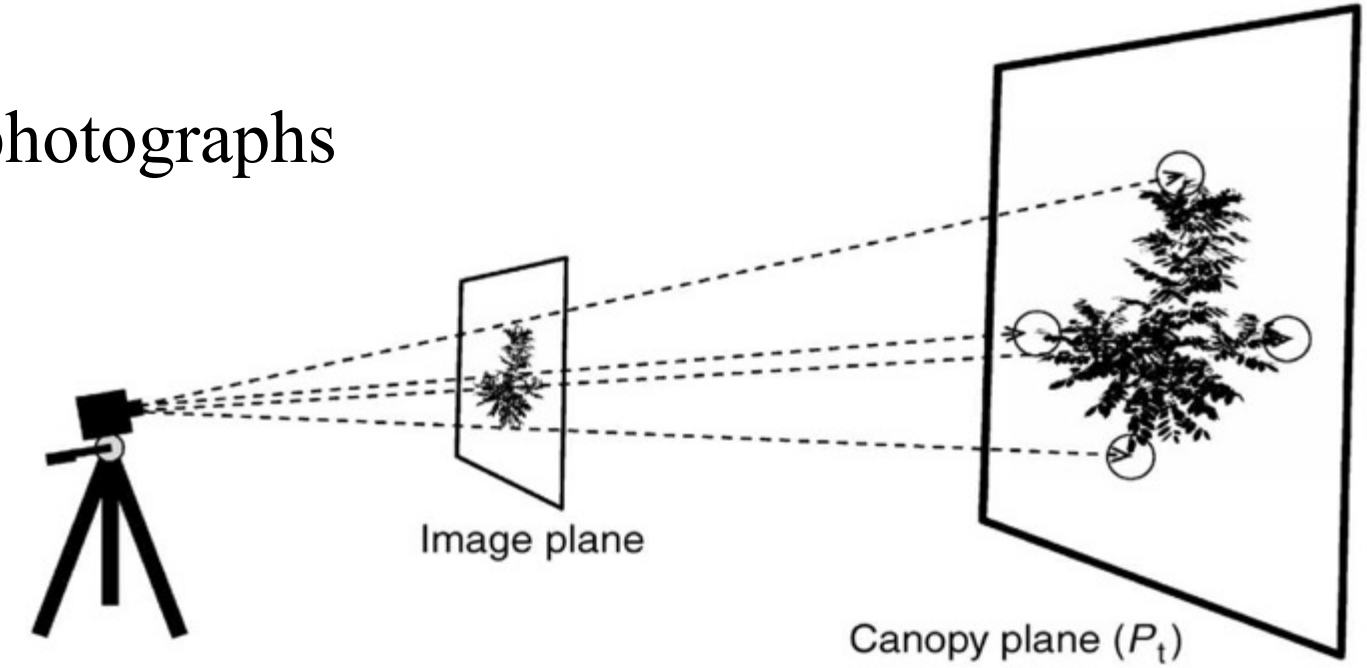
Various device types for range imaging

- Registered photographs
  - Visual Hull
- Structured lighting
  - Kinect
- Photogrammetry
- Laser Scanner (or LED camera)
  - Travel time based
  - Phase shift (Interferometry) based
- Etc..



Contactless method

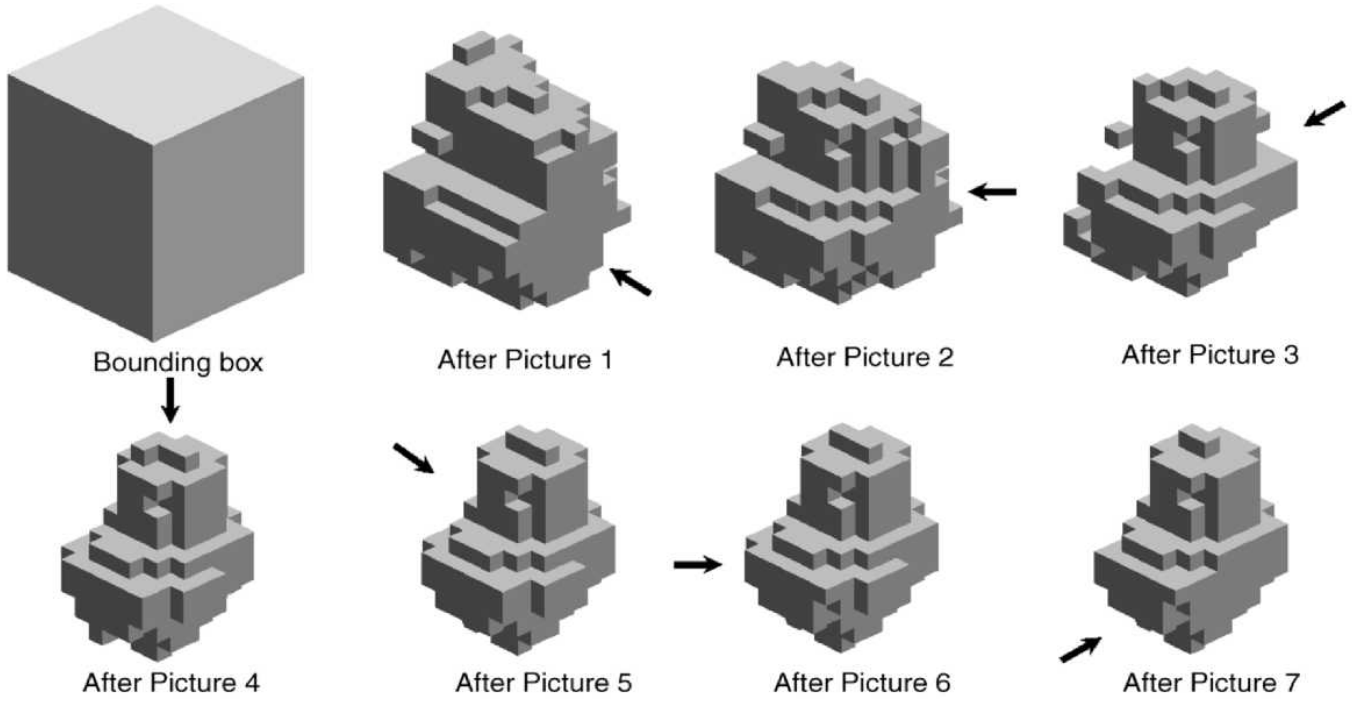
- Registered photographs



PHATTARALERPHONG, 2005, Tree Physiology

Contactless method

- Registered photographs : space carving algorithm

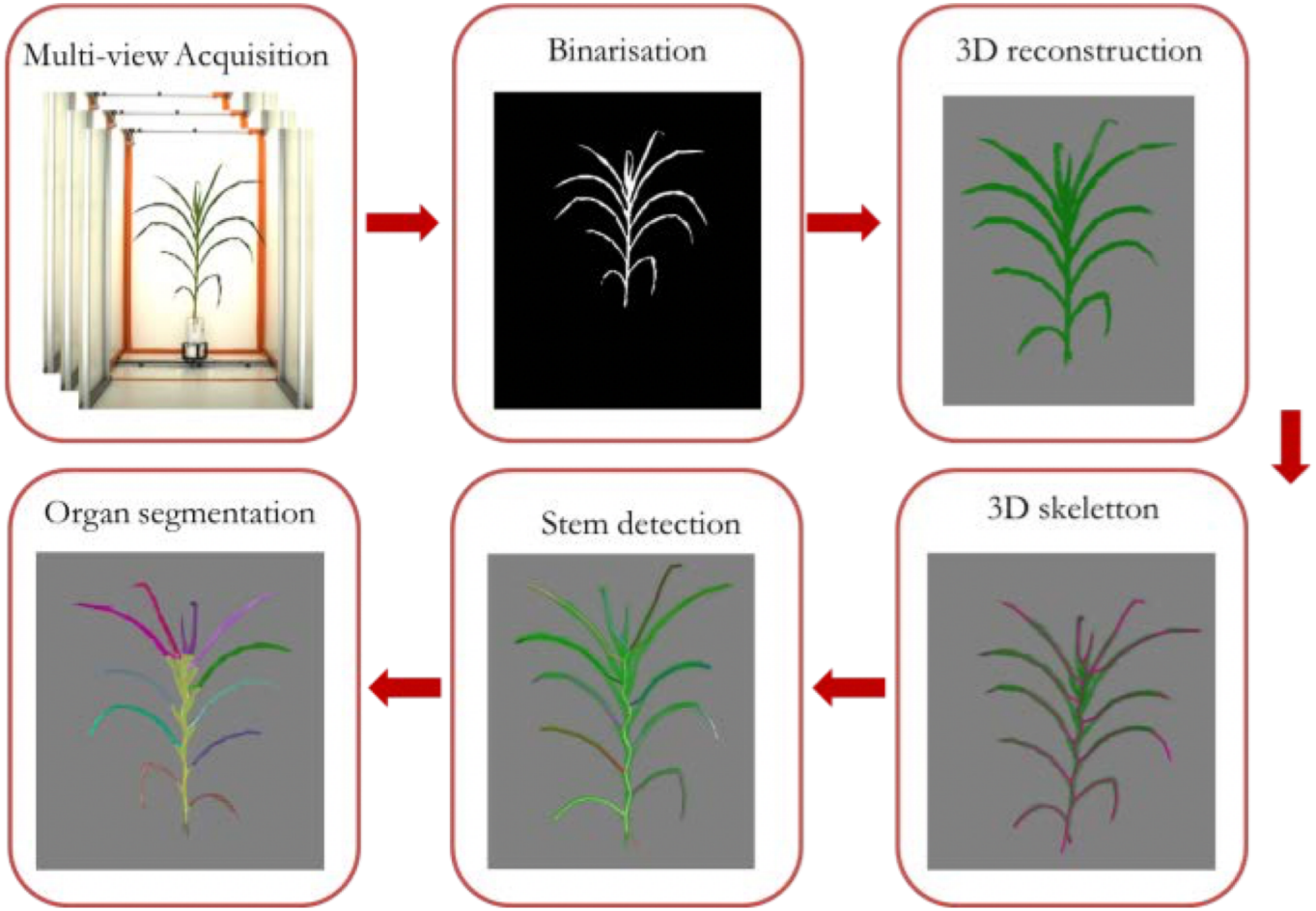


PHATTARALERPHONG, 2005, Tree Physiology

It allows to compute a volume.

Contactless method

- Registered photographs : automated pipeline in controled systems

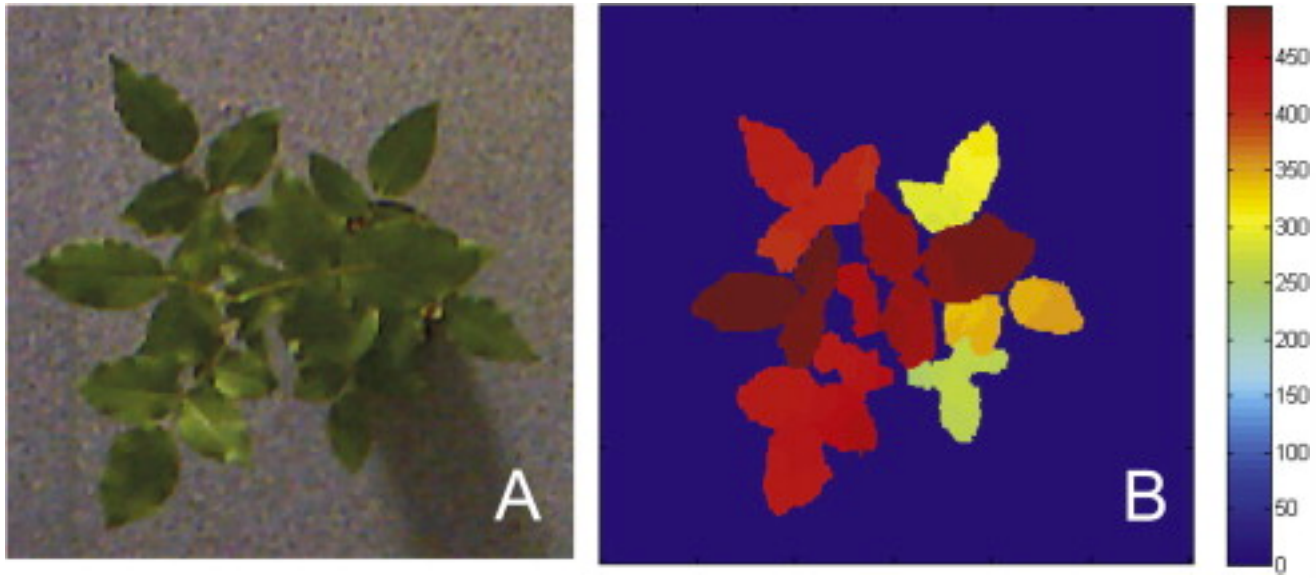


(Artzet et al., under revision)

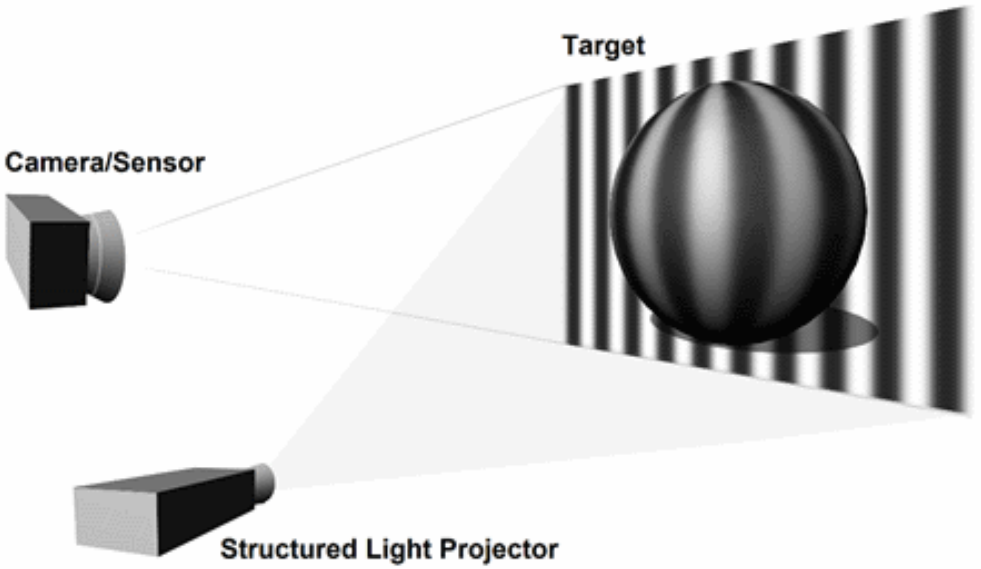
Reconstructing architecture of small plants

Contactless method

- Structured lighting



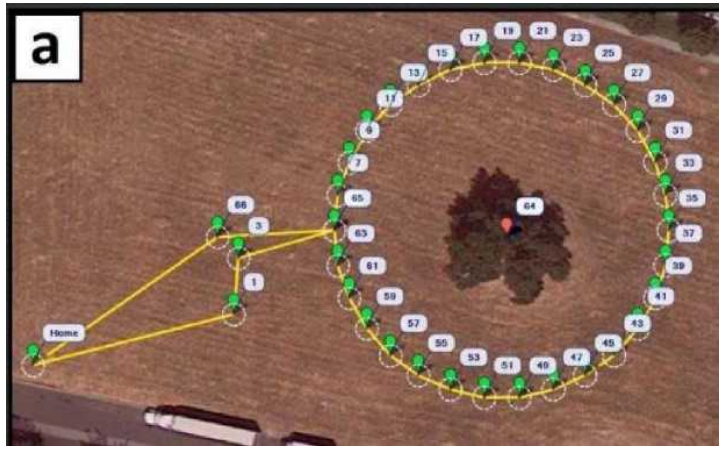
Chené et al., 2012.



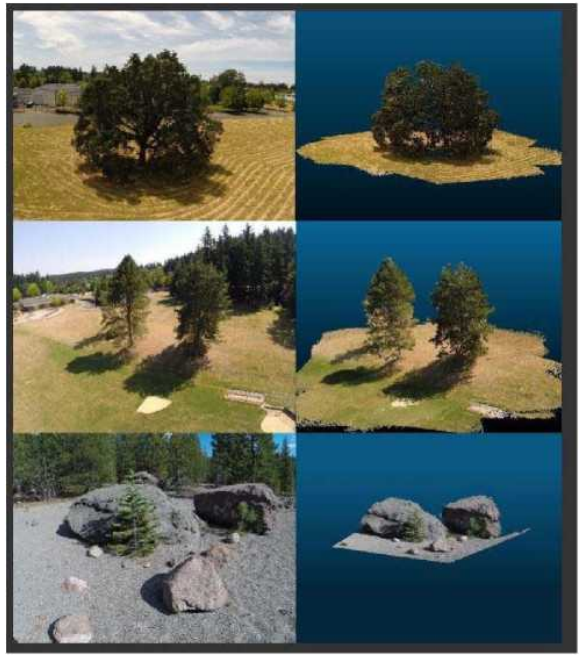
Reconstructing architecture of small plants

Contactless method

- Photogrammetry - 3D by triangulation



Gatziolis D, Lienard JF, Vogs A, Strigul NS (2015) 3D Tree Dimensionality Assessment Using Photogrammetry and Small Unmanned Aerial Vehicles. PLoS ONE10(9)



Precision depends on the number of views.
Need to tune the number of view on which a point should appeared.
Result in a point cloud.
Could allow estimating LAI, LAD, Volume, Height.

Contactless method

- Photogrammetry - 3D by triangulation

Faye, Saron et al., 2019

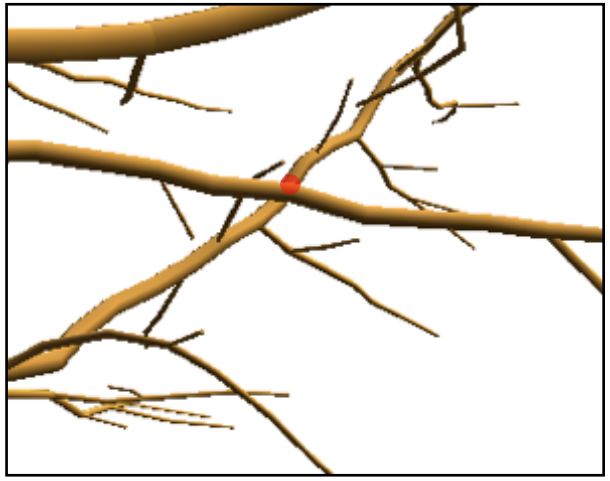
Scan from terrestrial laser

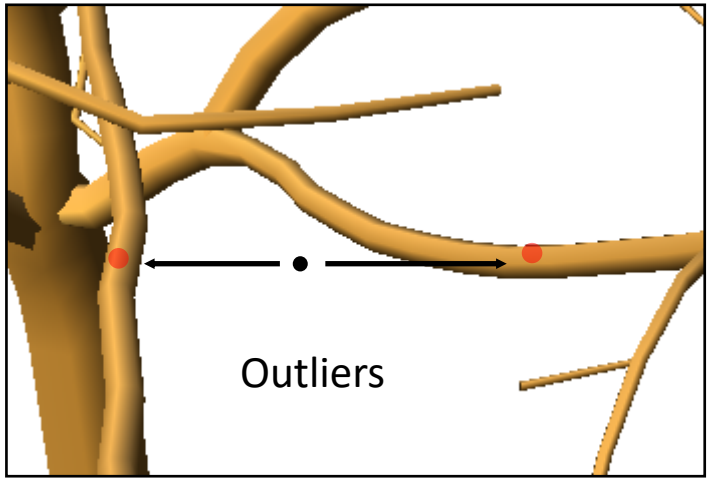
- Laser scanner devices acquire 3D images of a plant

Scan of plants

- Unstructured point set

- Several sources of noise :
  - Distance , Environmental condition (wind), Laser signal quantification, Laser footprint.





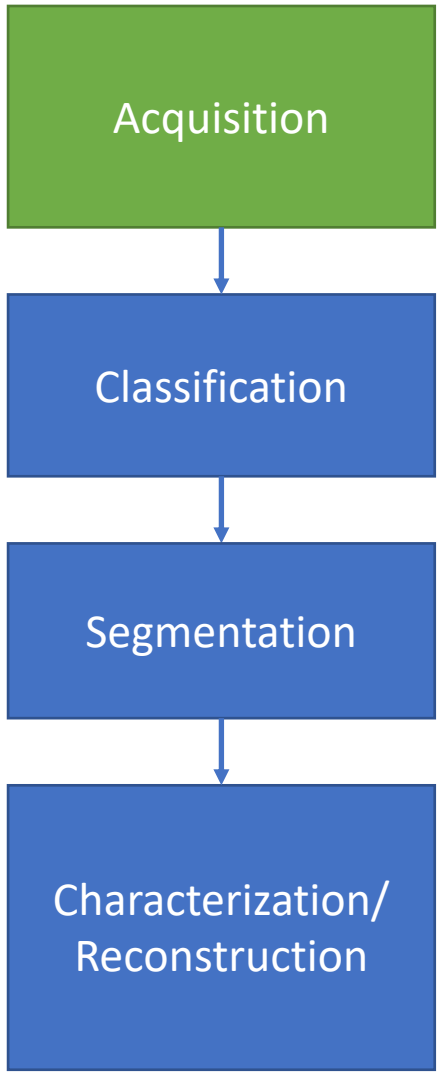
Point Patterns

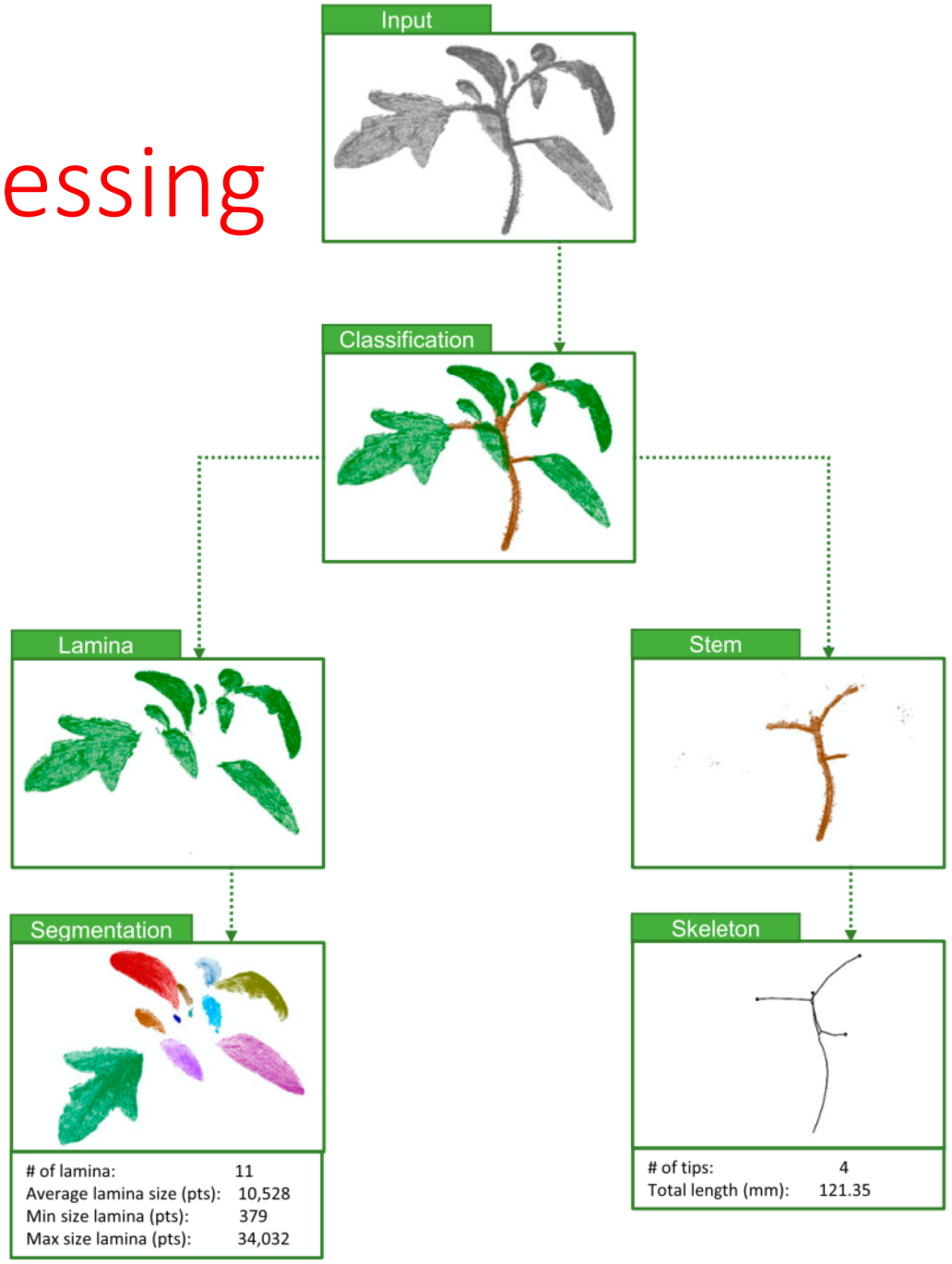
Dense data points
(trunk, big branches)

Sparse data points
(small branches, twigs)

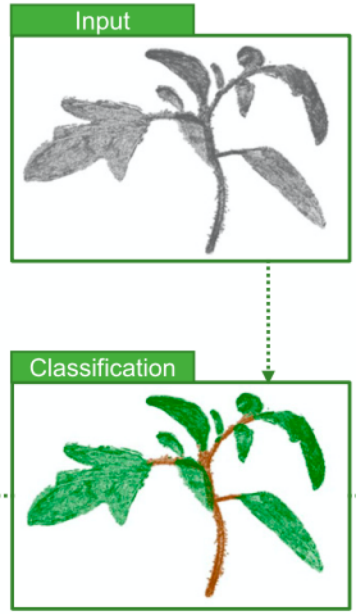
Incomplete data points
(occlusion)

Point cloud processing



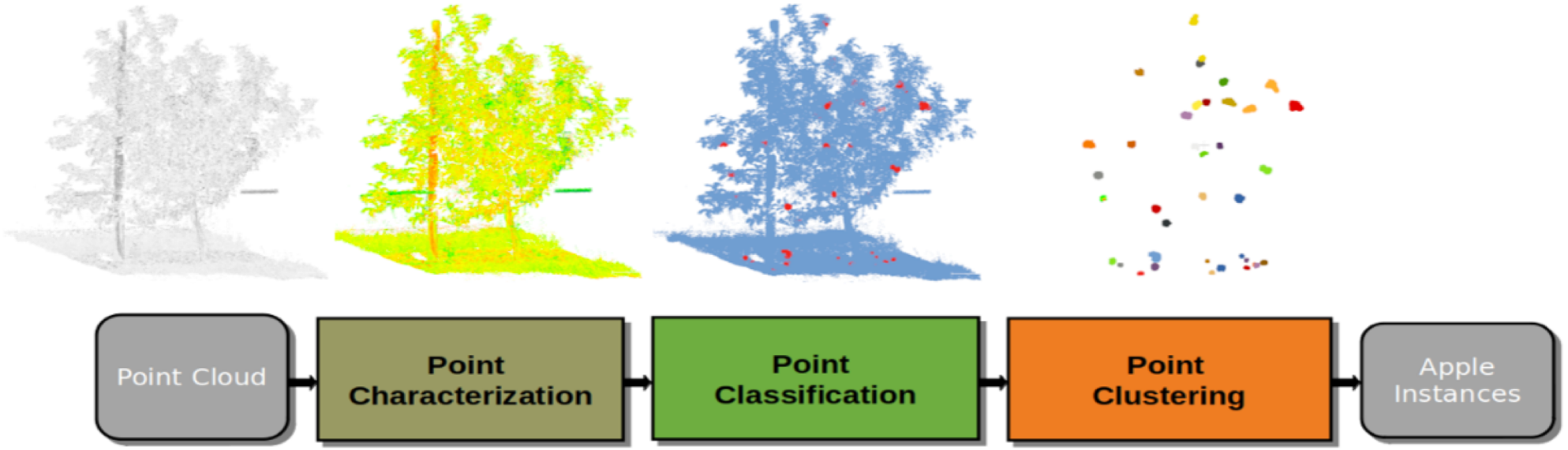


Ziamtsov and Navlakha , 2019



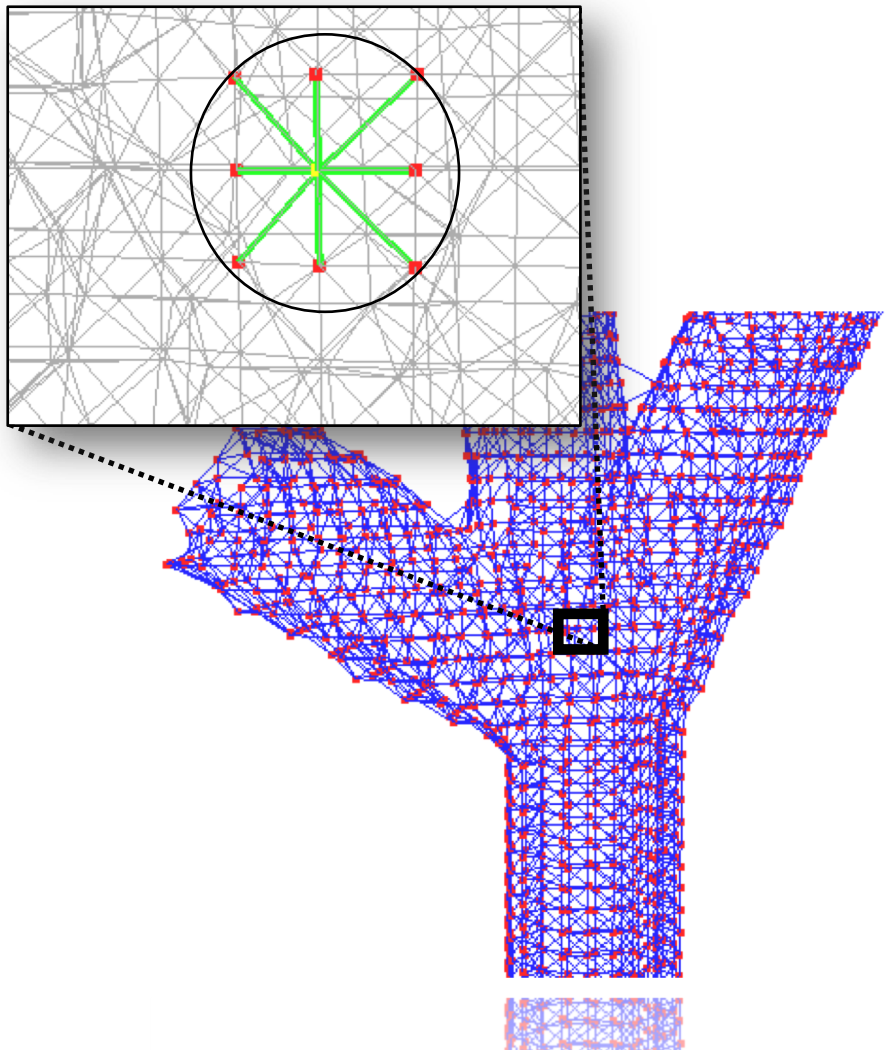
Classification and segmentation: Machine learning based pipelines

- Application on fruit detection (Artzet et al., 2020)

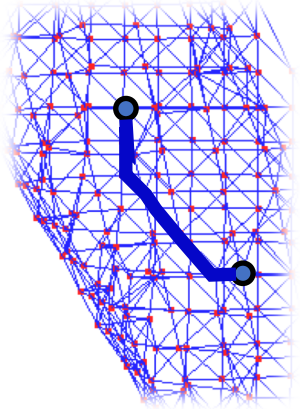


Points Local Connection

- Each point is connected to its k closest neighbors. This form the Riemannian graph L.



- Distance between 2 points can be redefined as length of shortest path between them.



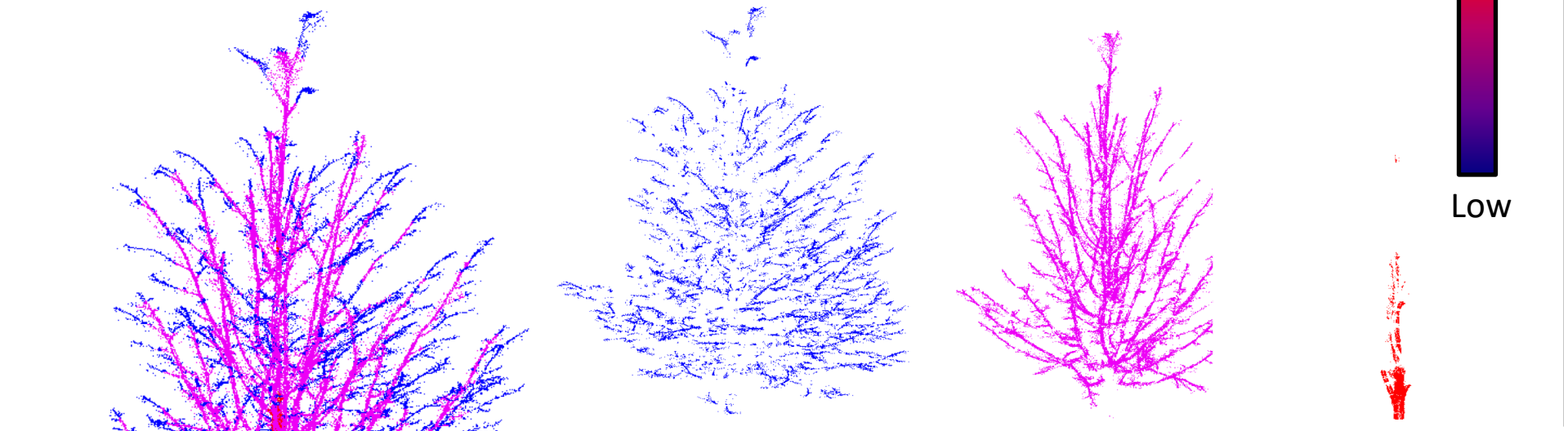
- The R- neighborhood of p_i is defined as points p_j whose distance of path to p_i on the graph L is smaller than R.

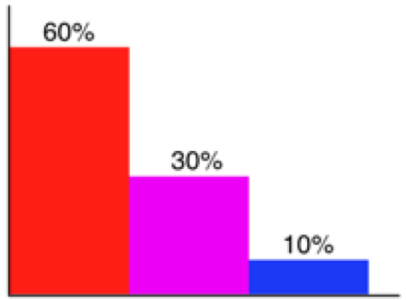
Distance on graph L
R=20

Points Local Density

- The local density depends on the number of points in the r-neighborhood. (Pauly et al, 02)

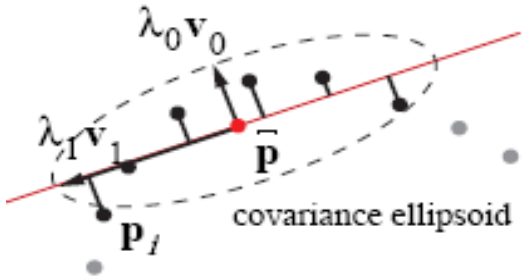
$$\lambda = \frac{k}{r^2}$$

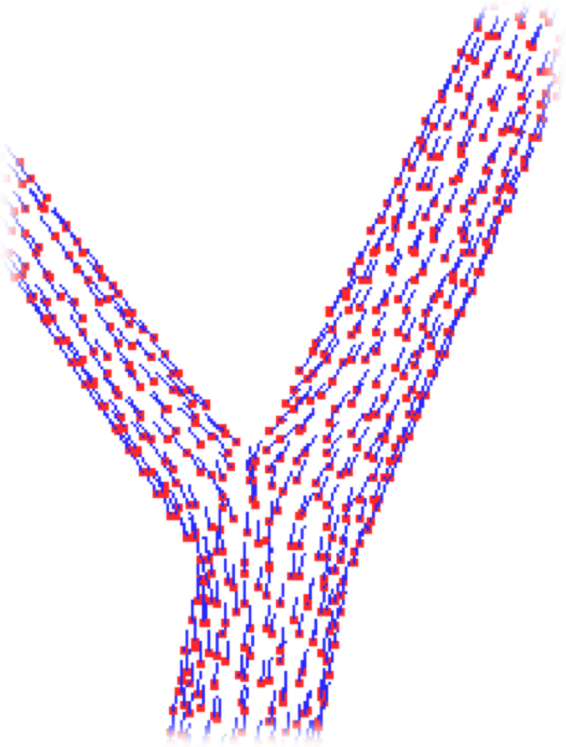


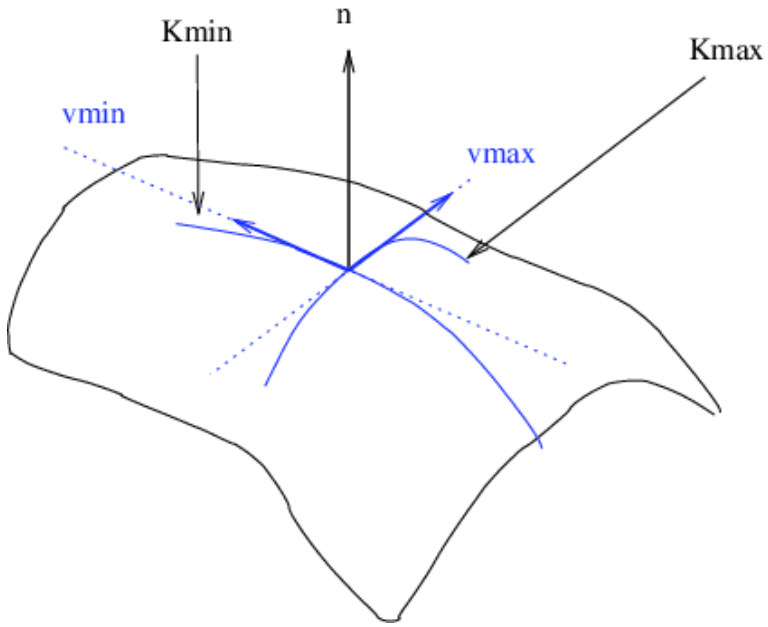


Points Local Orientation and Curvature

- For each point, a Principal Component Analysis is made on its R-neighborhood. Principal direction gives local orientation of the point set.







Using spatial and radiometric features for segmentation

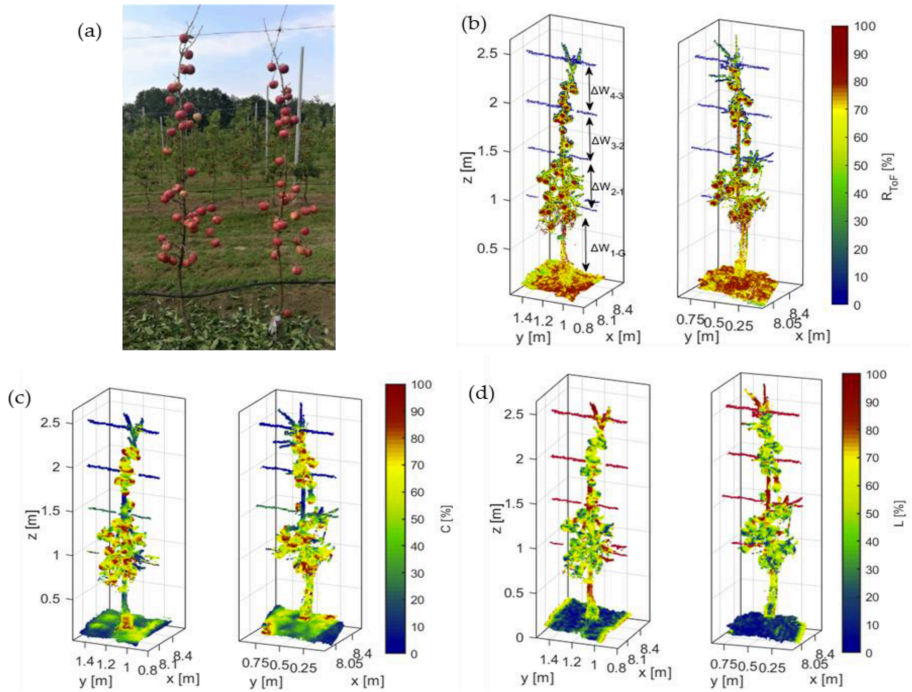
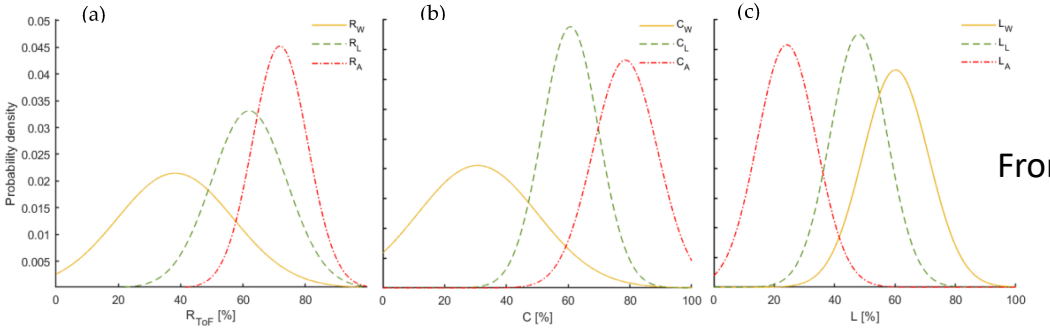


Figure 4. Representation of 3D point clouds of (**a**) RGB image (**b**) reflectance (R_{ToF}) [%], (**c**) curvature (C) [%] and (**d**) linearity (L) [%] in defoliated trees at $DAFB_{120}$.



From Tsoulias et al., 2020

Figure 5. The probability density of (**a**) calibrated reflectance intensity (R_{ToF}) [%], (**b**) curvature (C) [%], and (**c**) linearity (L) [%] for wood, leaves, and apples.

Toward multispectral LiDAR (foliage vs wood)

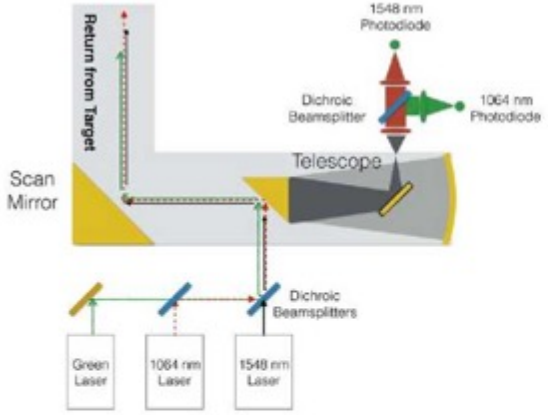


Fig. 1. Instrument schematic. Thin lines represent the outgoing coaxial beams. Gray lines represent the FOV of the instrument and the path of the observed returns. The continuous wave green laser serves as a marker and is not recorded.

From Douglas et al., 2015

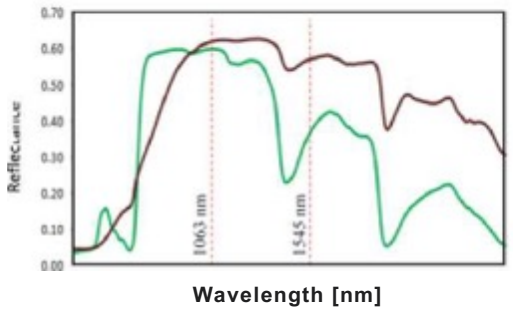
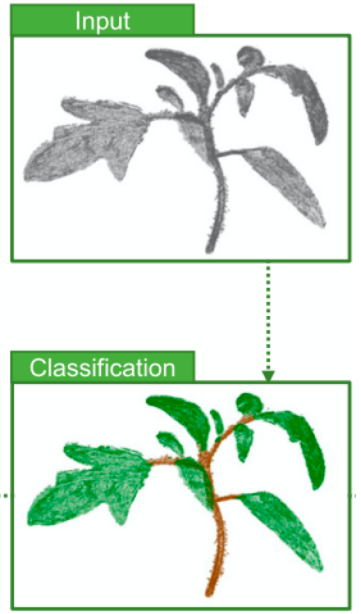
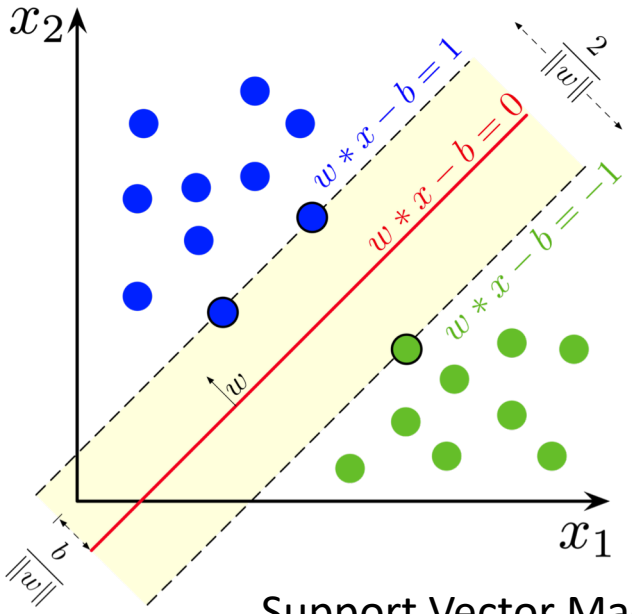


Figure 1. Spectral reflectance of an oak leaf (green) and oak bark (brown). From Danson et al., 2018

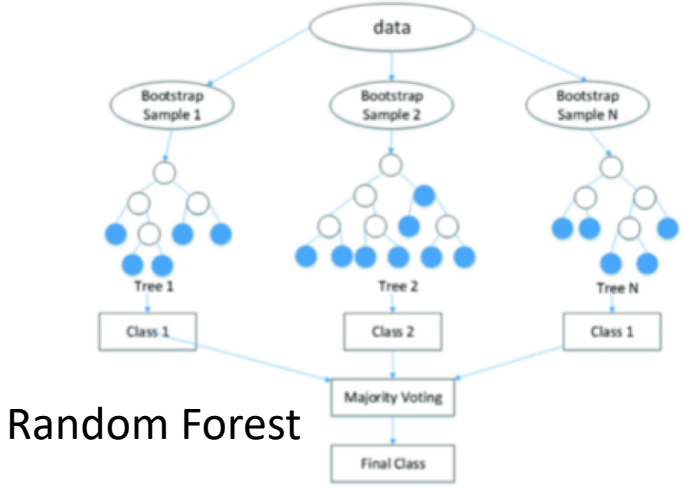


Classification: Machine learning based pipelines

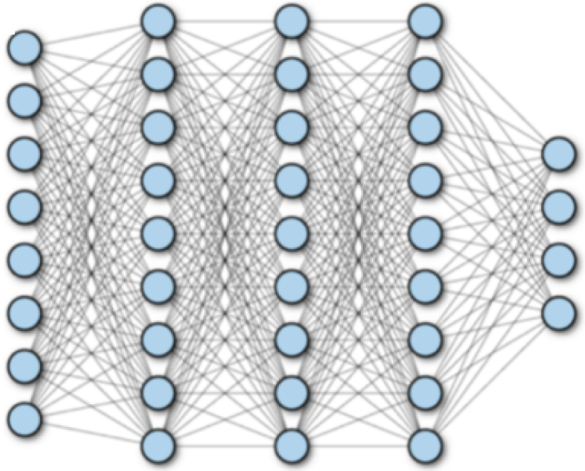
- Classification points of plant scan based on machine learning (Ziamtsov et al., 2019, Artzet et al., 2020)



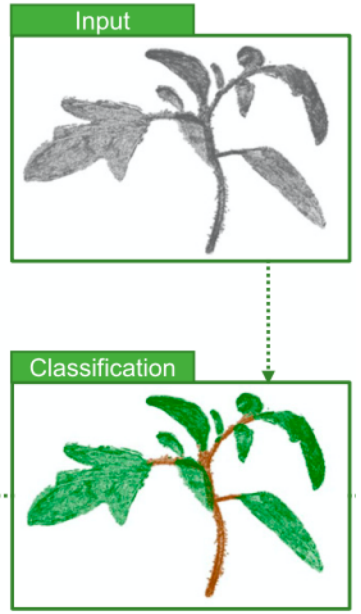
Support Vector Machine



Random Forest

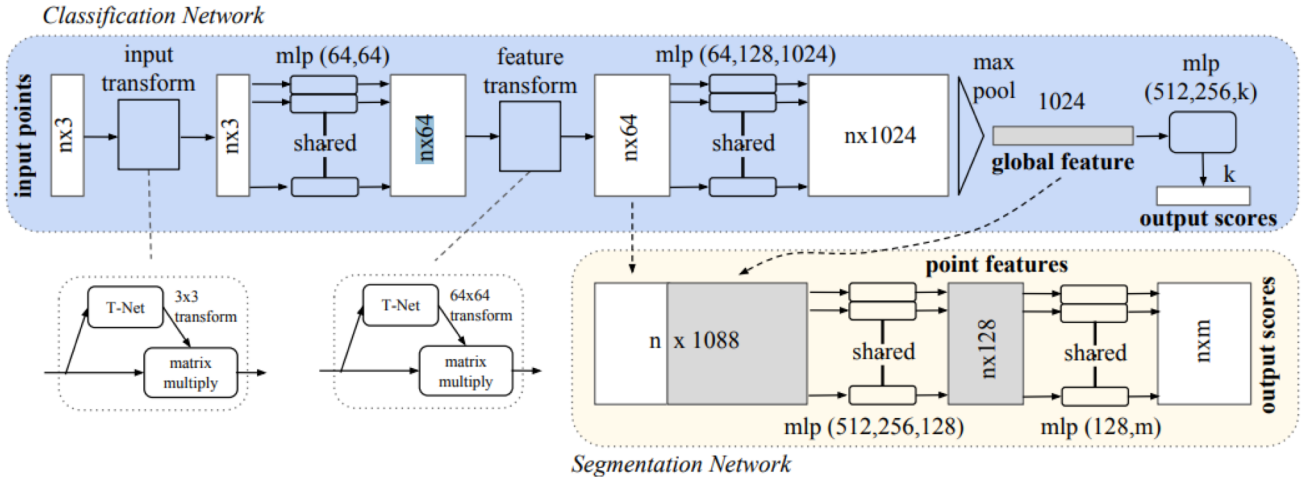


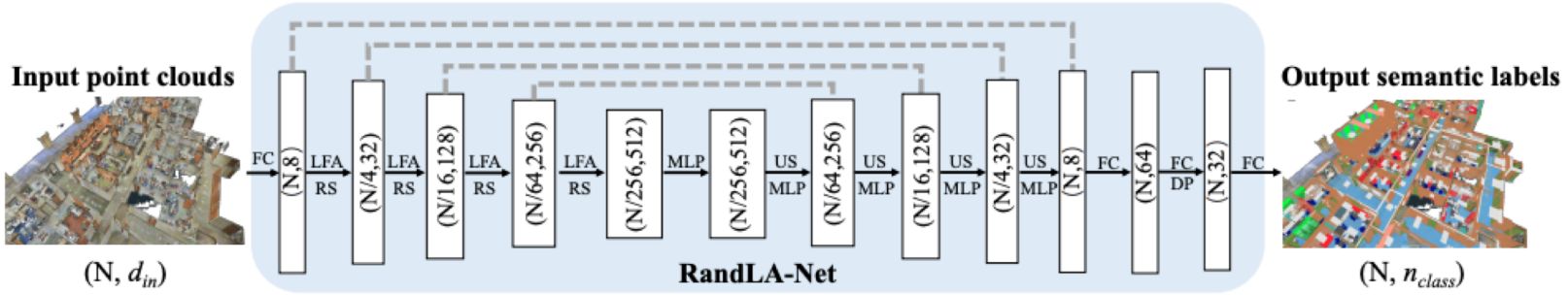
Neural Network

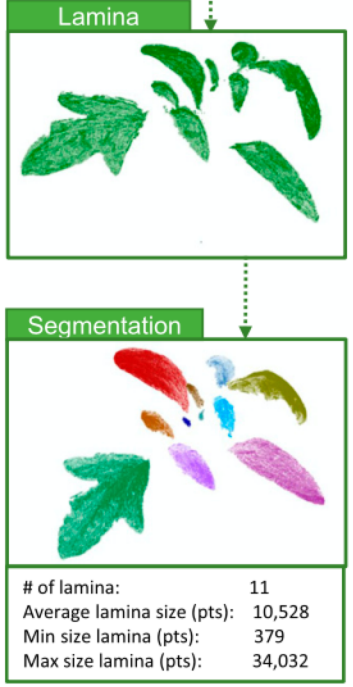


Classification: deep learning based pipelines

- Classification based on deep learning such as PointNet (Qi et al., 2016) or RandLaNet (Hu et al., 2019). Tested on plant in (Artzet et al., 2020)

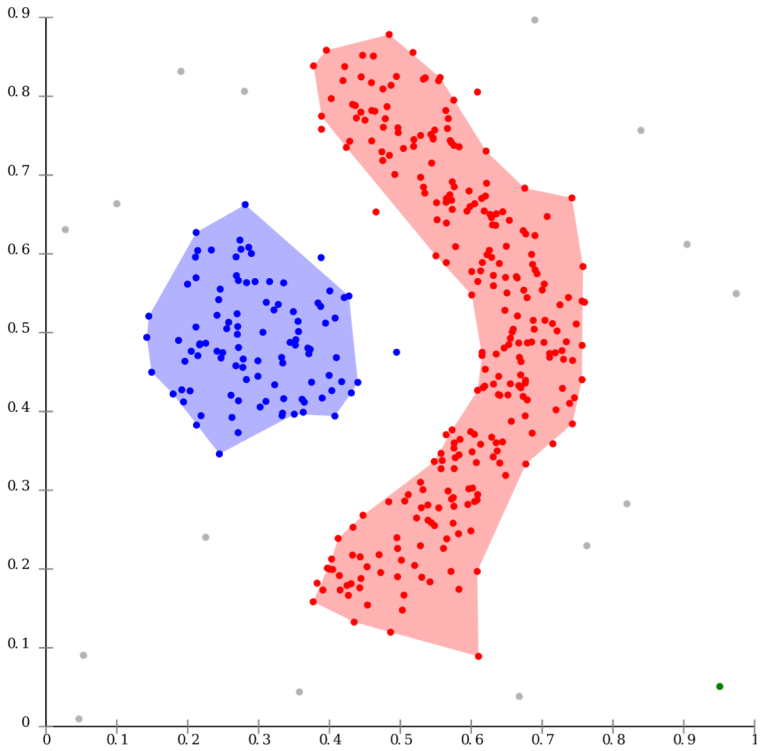


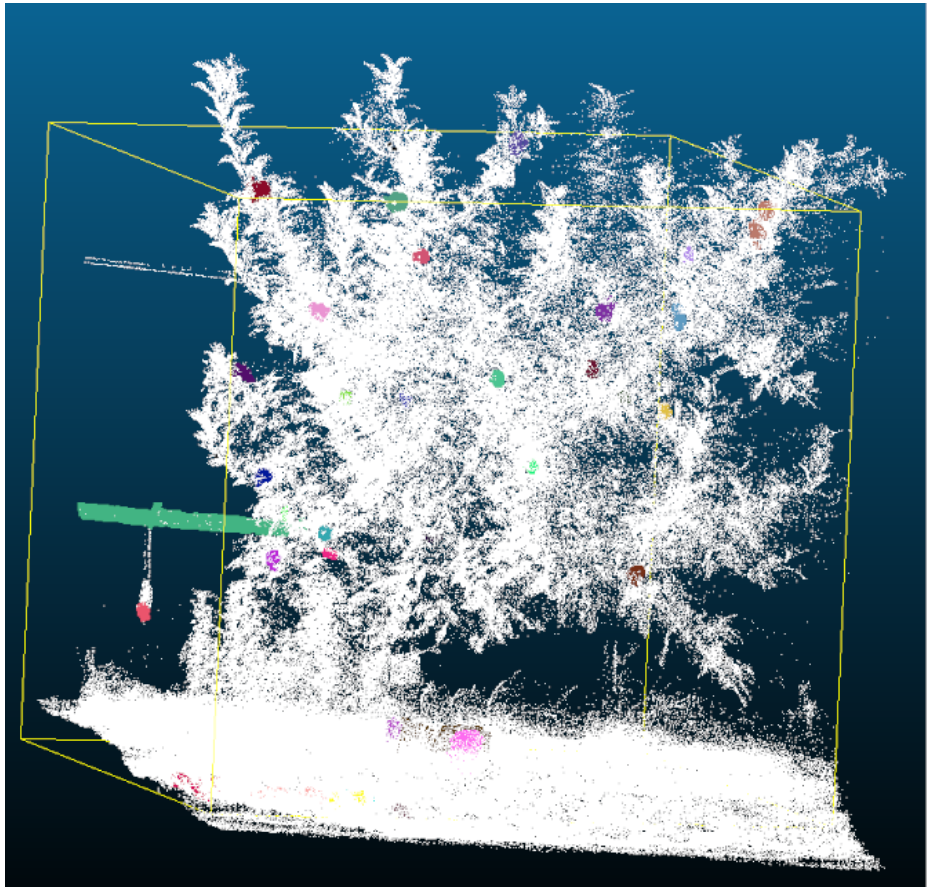


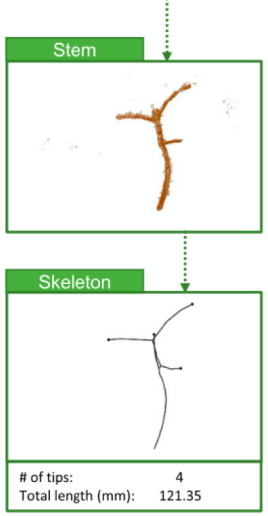


Segmentation: clustering

- DBScan algorithm
  - Growing regions
  - Non linear

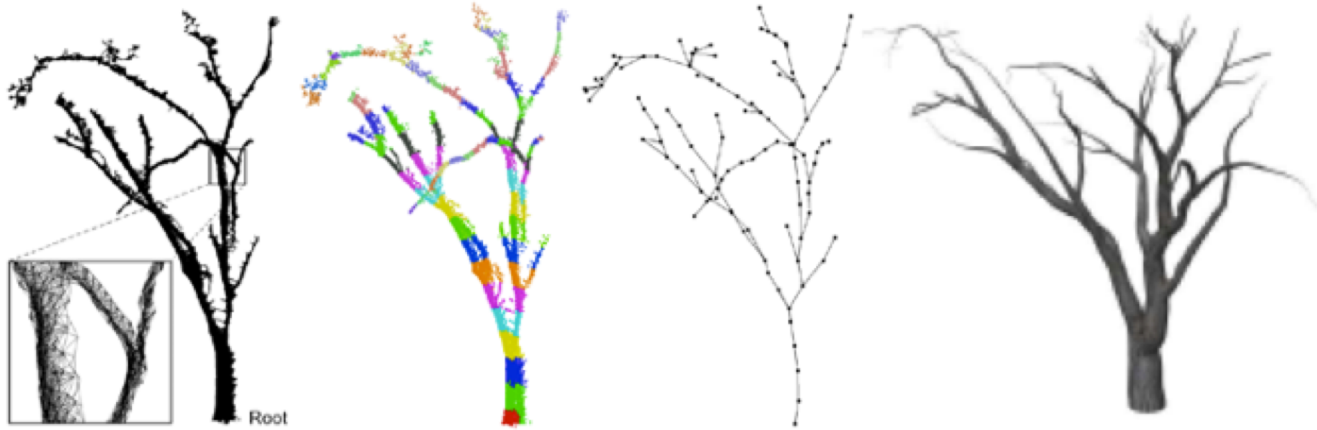




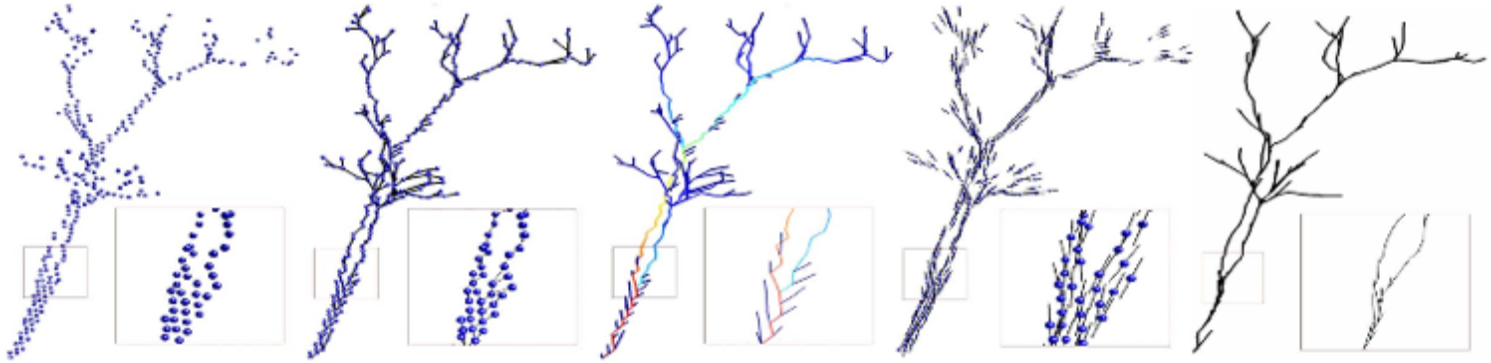


Reconstructing plant architecture based on 3D-points

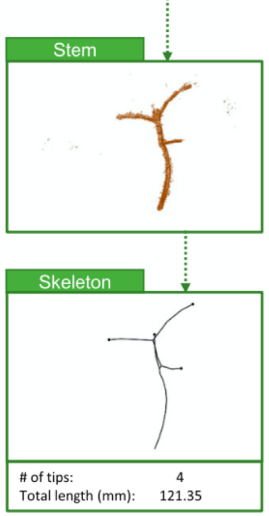
- Clustering of point set (Xu *et al.*, 07).



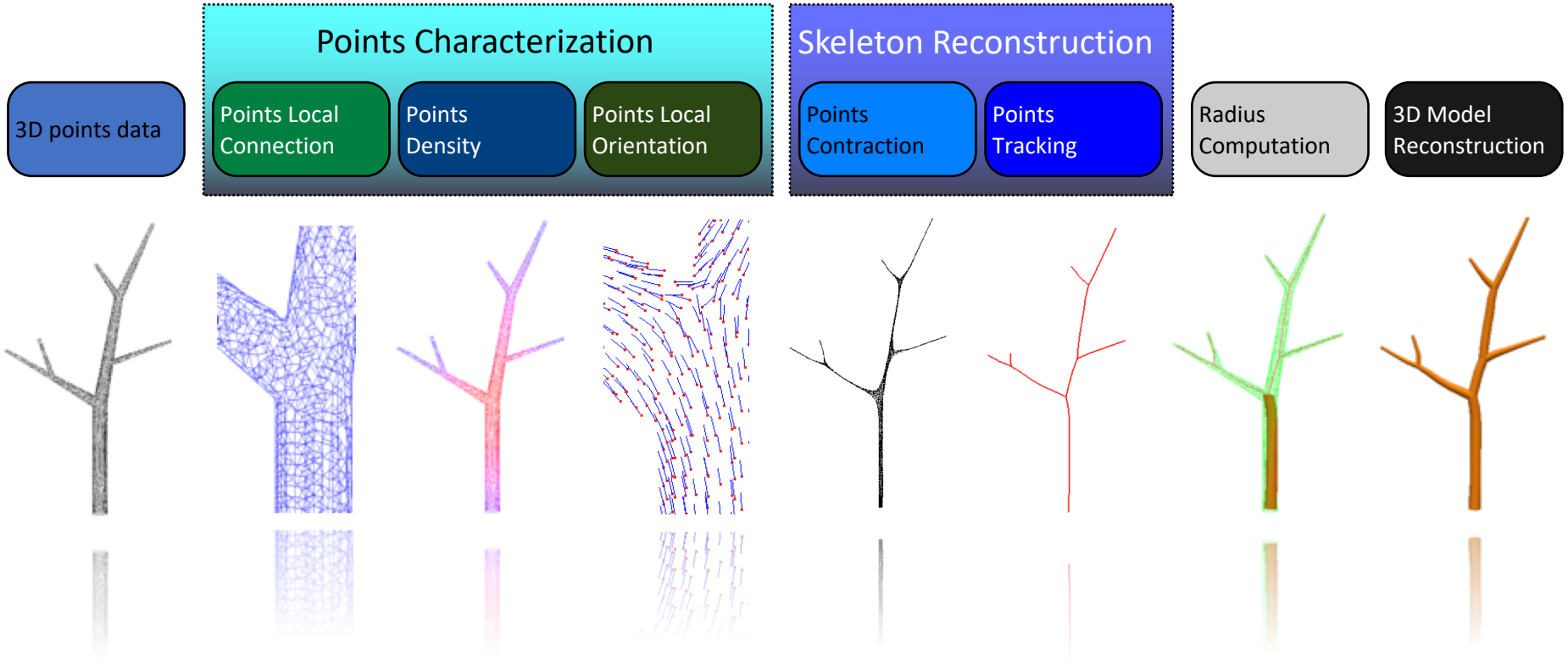
- Global optimization and point alignment to reconstruct branching systems (Livny *et al.*, 10).



(see TP1)



A Pipeline for Reconstruction
3D Architecture (Preuksakarn et al., 2013)



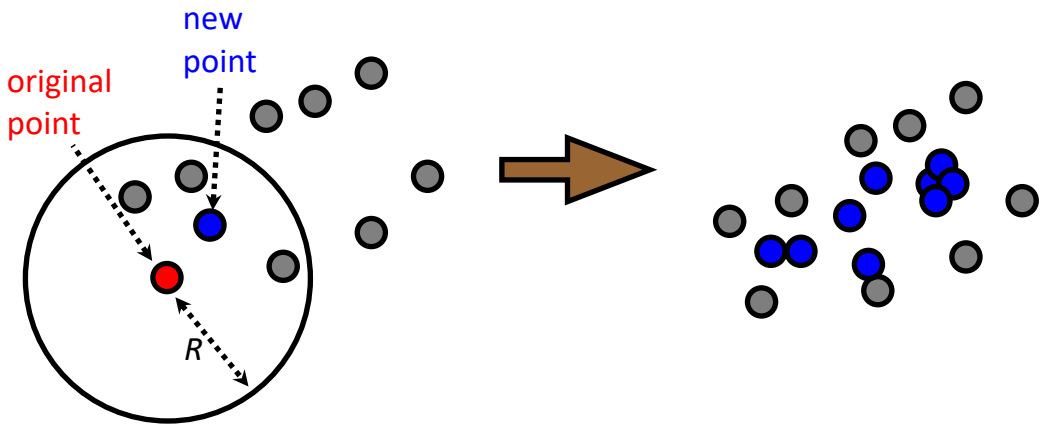
(see TP1)

Points Contraction

- Shift the points from the border of the shape toward its center (Riccardo et al, 99).

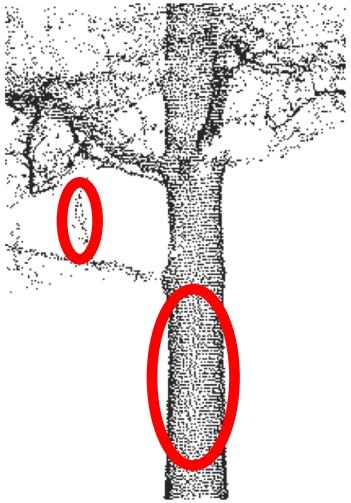
$$c_i^R = \frac{\sum_{p_j \in S_i^R} p_j}{|S_i^R|}$$

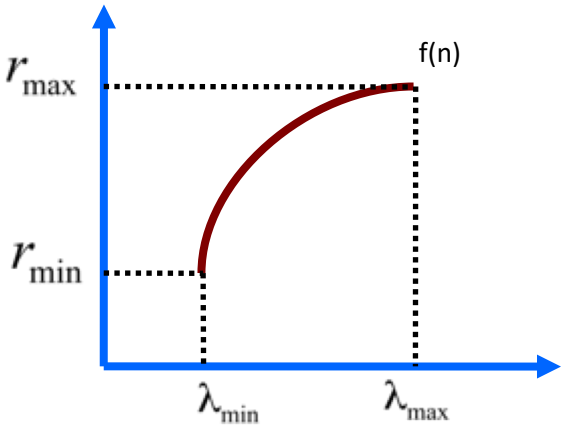
$$P \rightarrow P^R = \left\{ c_i^R \right\}$$



Adaptive Distance

- Distance of contraction will be determined according to the local density and user defined function.

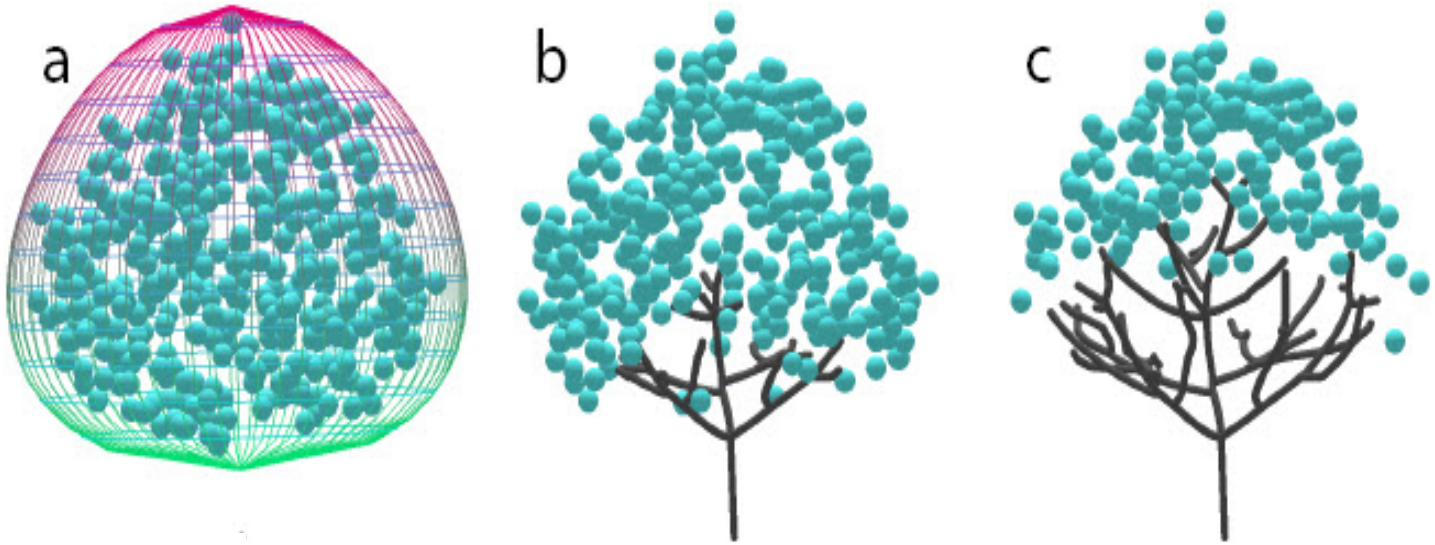




Use density information to discriminate

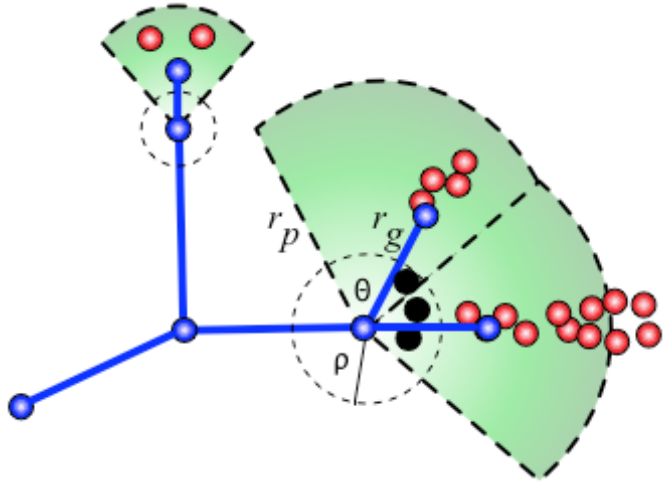
Point Tracking Algorithm

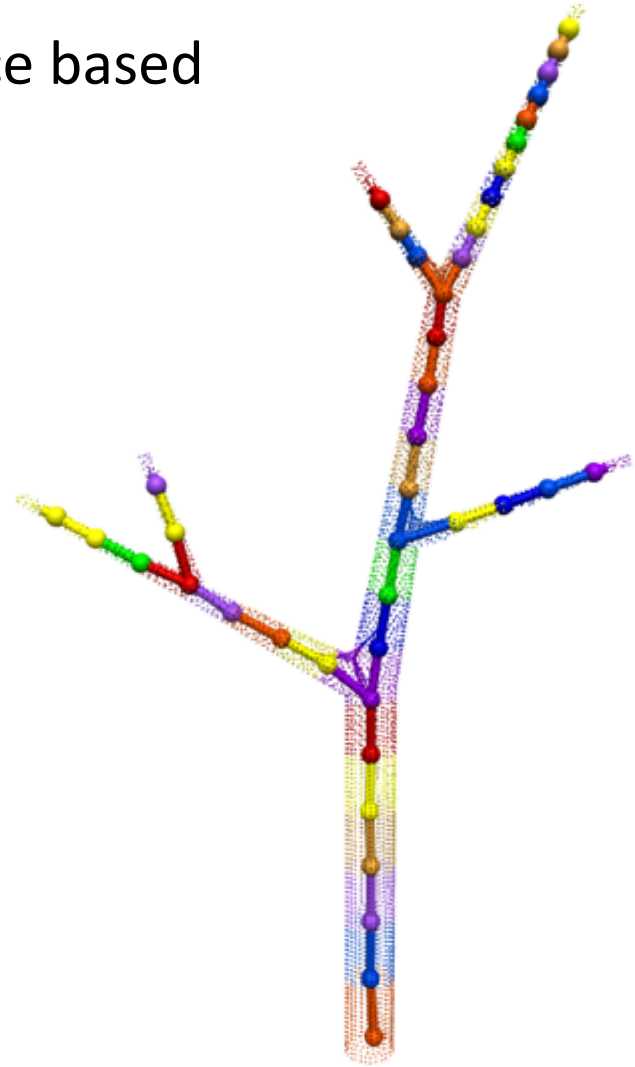
- Based on the Space Colonisation Algorithm (Runions et al., 07, Palubicki et al., 09). The branching structure of trees try to reach the attraction points.



Adaptive Point Tracking

- The growth, influence and kill distance based on local density.





- The colonization will be done in the Riemannian graph space.

Reconstruction

Estimation of the diameter

- The radius at each node is estimated using the pipe model [Shinozaki et al. 64].

$$d_i^p = d_j^p + d_k^p$$

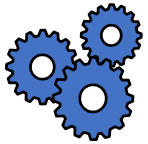
$$p = \frac{\log |n_{f_i}|}{\log d_i - \log d_{f_i}}$$

Results

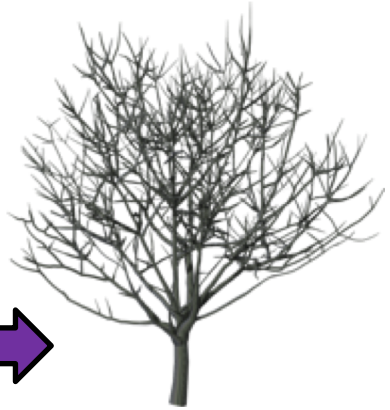
Results

Problem of the quantitative assessment of automatic reconstruction

laser scan



Automatic reconstruction



Global Comparison

- Indirect index comparison (Côté *et al.*, 09, *etc.*)
  - Wood content, foliage area, crown volume, etc..
  - Reflectance signature, transmission properties, etc..

(Pradal, Boudon et al, 09)

⇨ Evaluate indirectly the accuracy of the structure

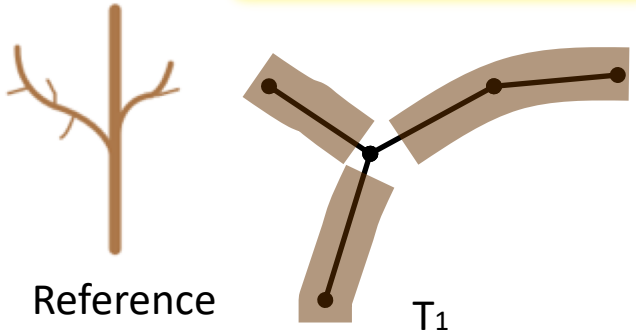
Structure Comparison

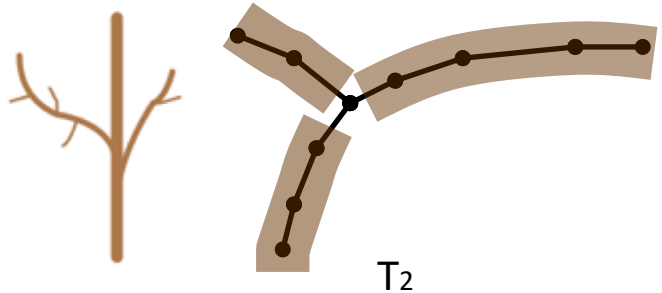
- Finding geometrical and structural similarities

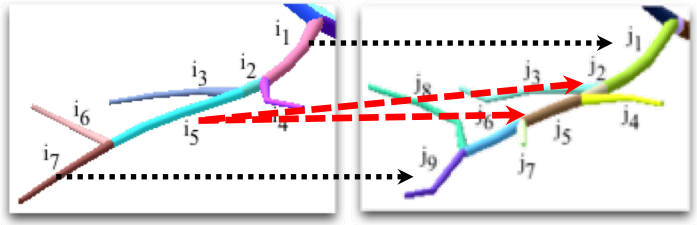
Homogenizing structures

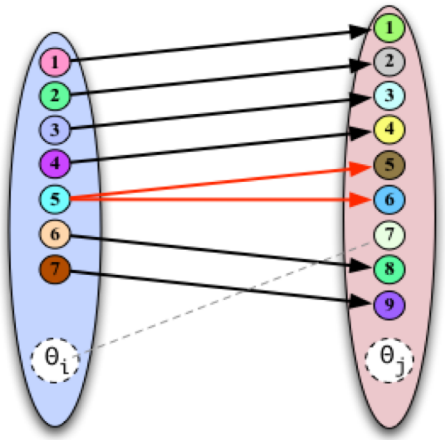
Geometrical mapping

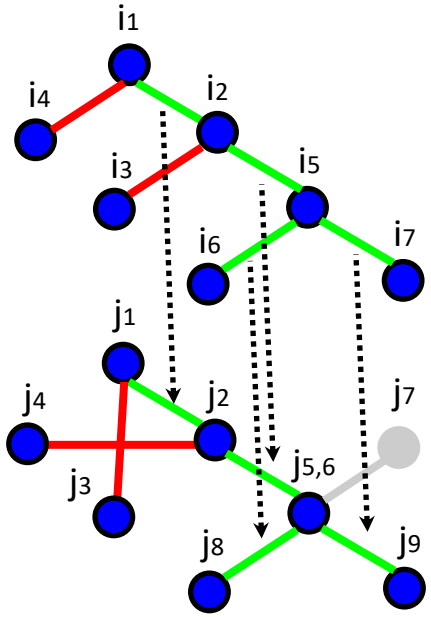
Topological mapping











$$D_G(T_1, T_2) = \frac{2\left|M^G\right|}{|T_1| + |T_2|}$$

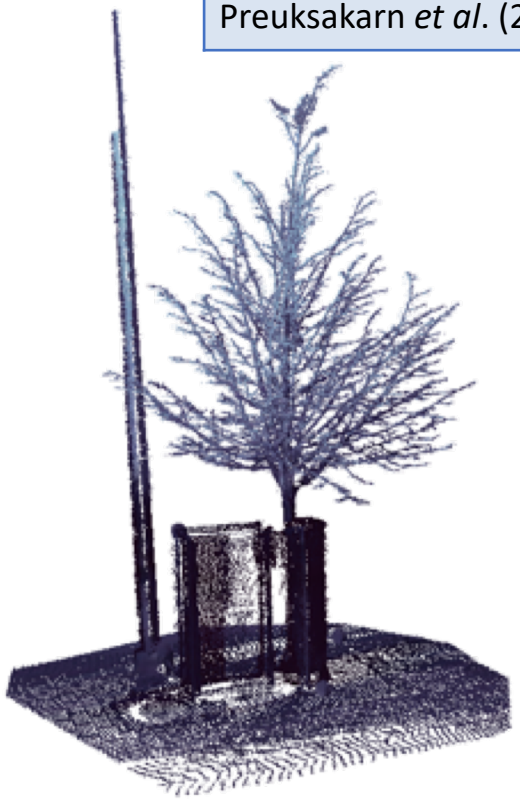
$$D_T(T_1, T_2) = \frac{2\left|M^T\right|}{|E_1| + |E_2|}$$

(Boudon et al., 2012)

Comparison of methods of the literature

- Comparative evaluation of (Xu *et al.*, 07), (Livny *et al.*, 10) and (Preuksakarn et al., 10).

Method	Mean Point Distance (mm)	Volume (Ref: 13.17m²)	D_G	D_T
Xu *et al*. (2007)	12.55	12.76	0.81	0.87
Livny *et al*. (2010)	6.49	12.7	0.69	0.65
Preuksakarn *et al*. (2010)	7.26	13.3	0.90	0.72

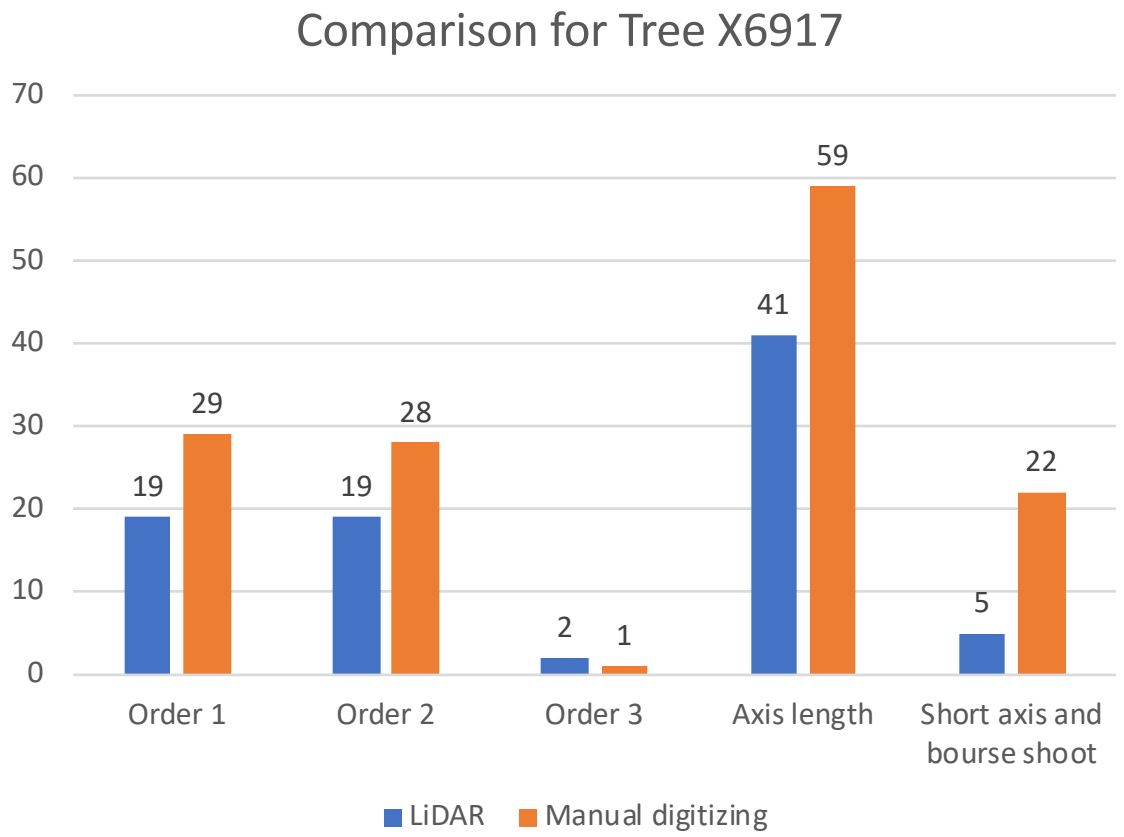


Xu *et al.*, 07

Livny *et al.*, 10

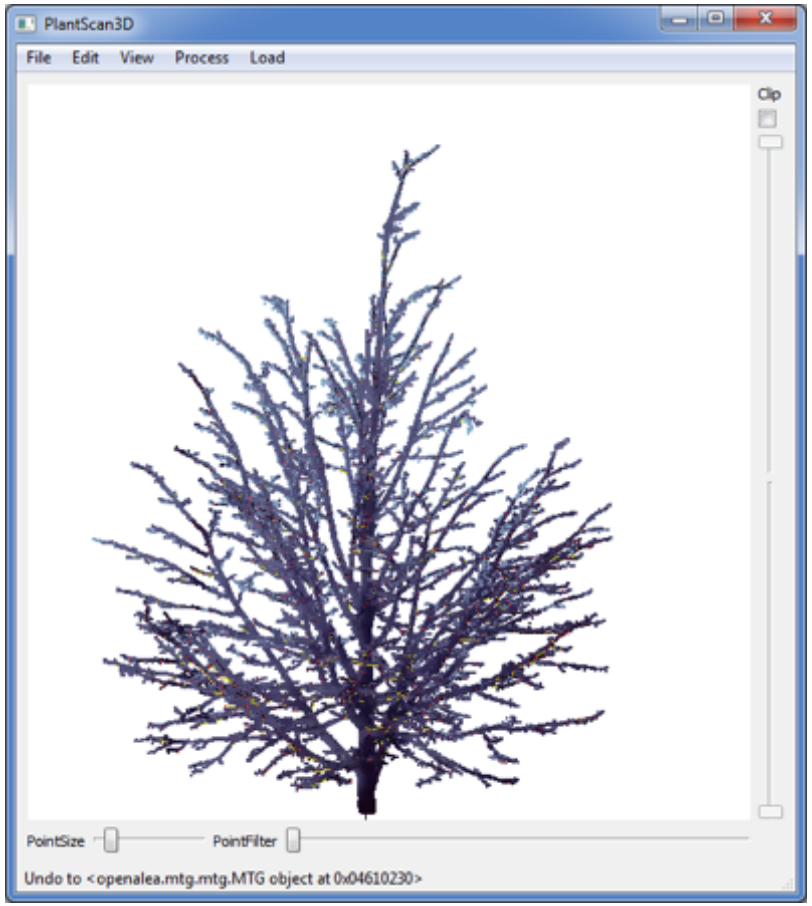
Preuksakarn *et al.*, 10

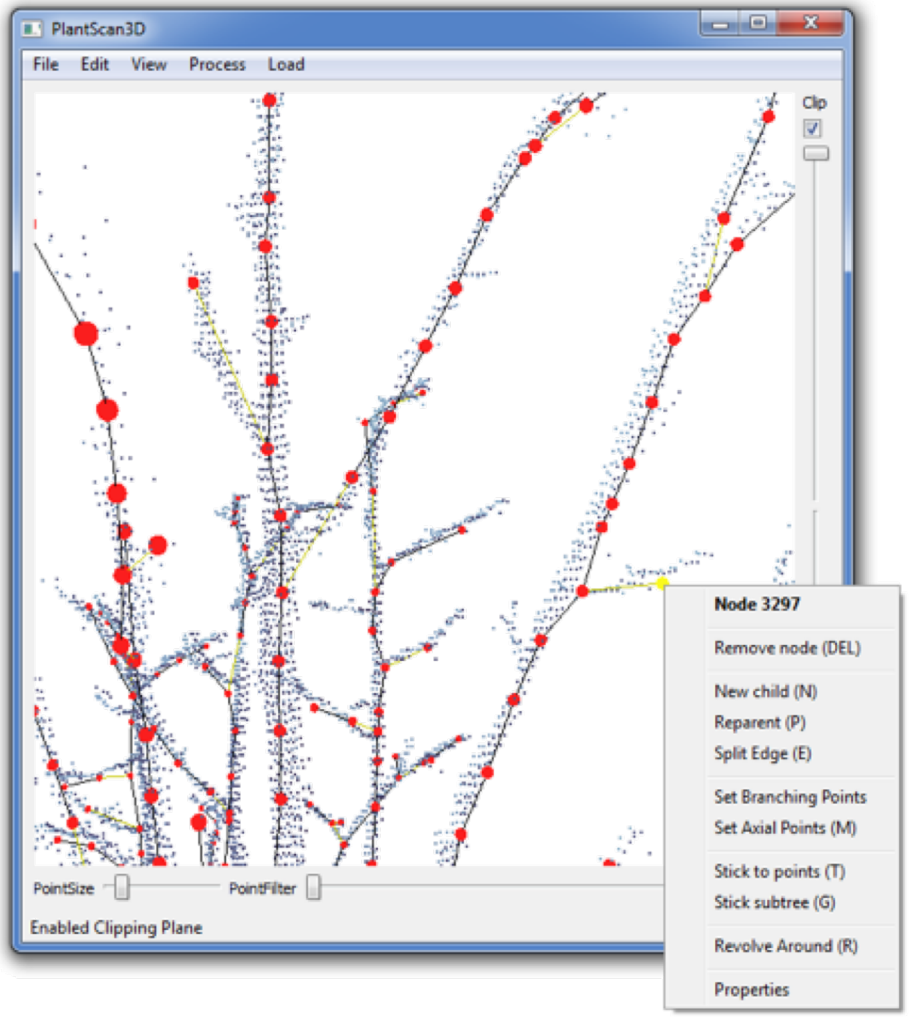
Comparing reconstructions from LiDAR and magnetic digitizing



Differences come mainly from short branches and bourse shoot.

Editor of plant architecture from laser scans





See TP

Foliage reconstruction based on allometric relationship

From Delagrange et al., 2011

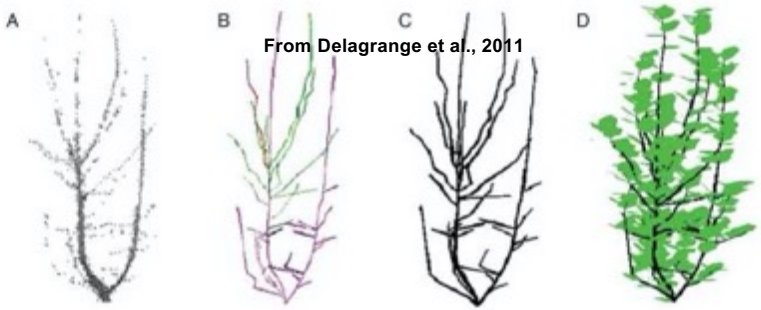
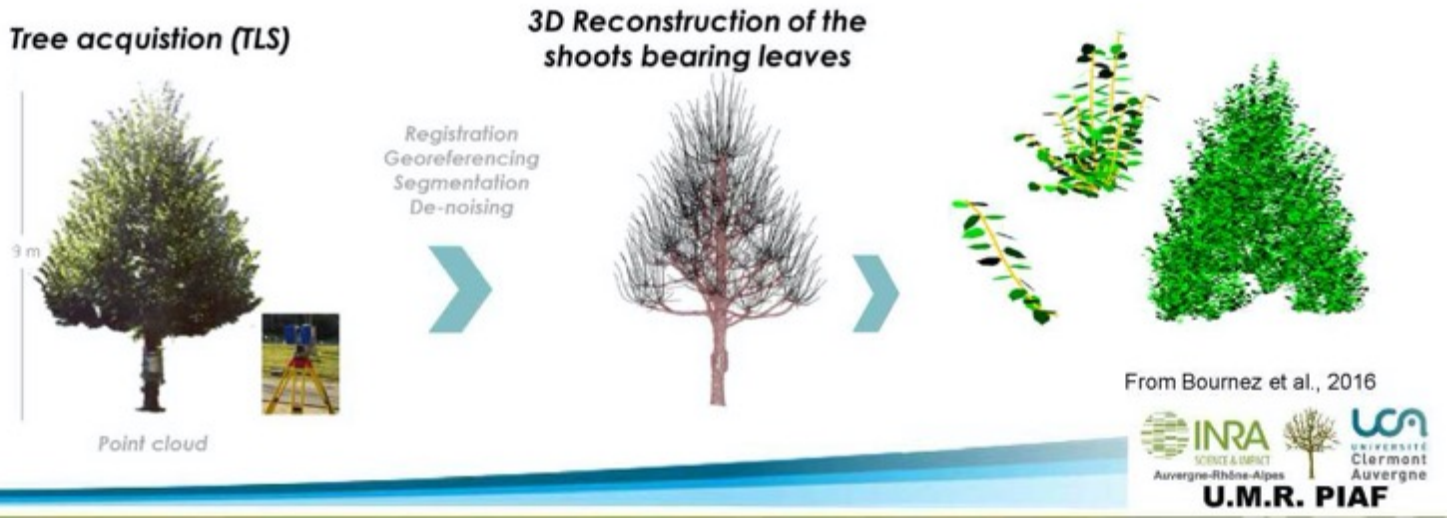
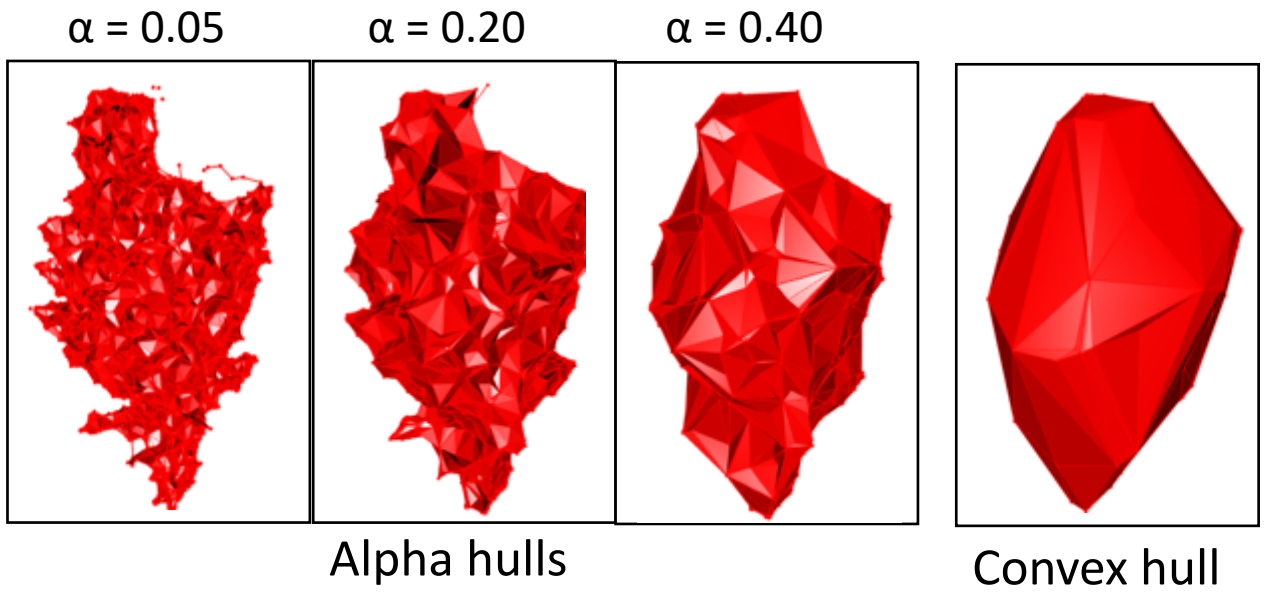


FIG. 2. Main steps of crown reconstruction from T-LiDAR scans. (A) Registered point cloud of the leaf-off scene (B), reconstructed skeleton, (C) pipe representation with reconstructed radius (D) and positioned leaves on the reconstructed pipe representation.

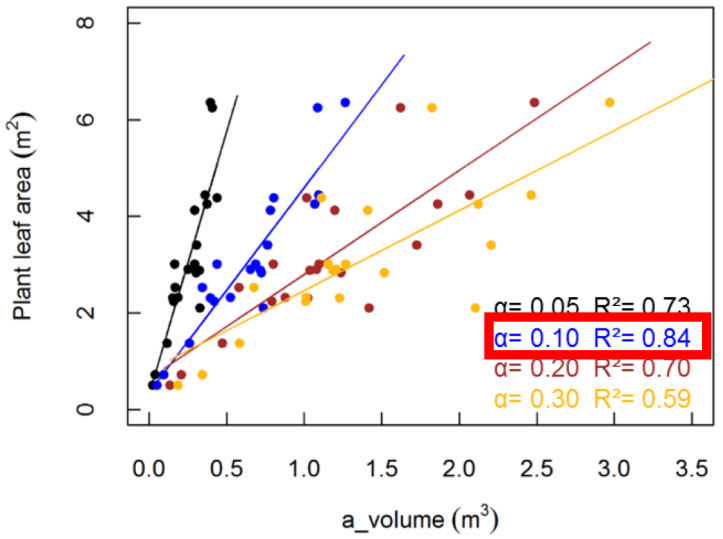


Foliage estimation based on allometric relationship

- Estimation of alpha volume (a_volume)



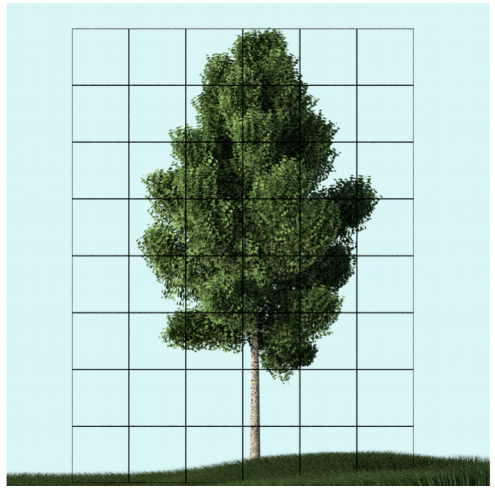
- Relation with foliage area

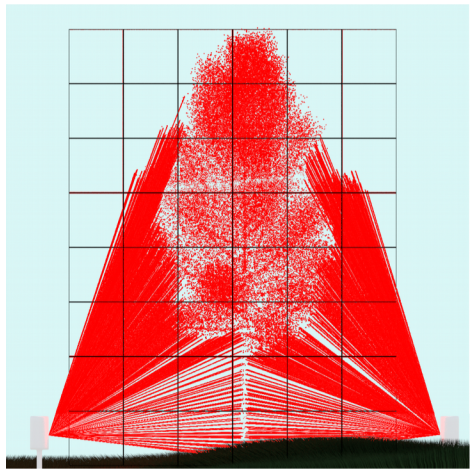


(Pallas et al., 2018)

Voxelization based foliage reconstruction from Lidar

- Estimation of leaf area from transmittance of voxels from input and output lidar rays in each voxels

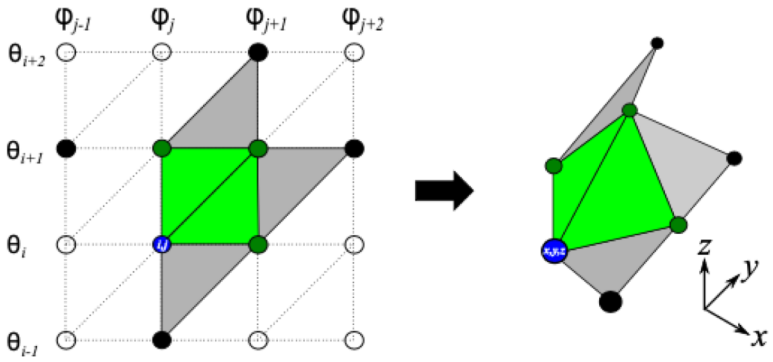


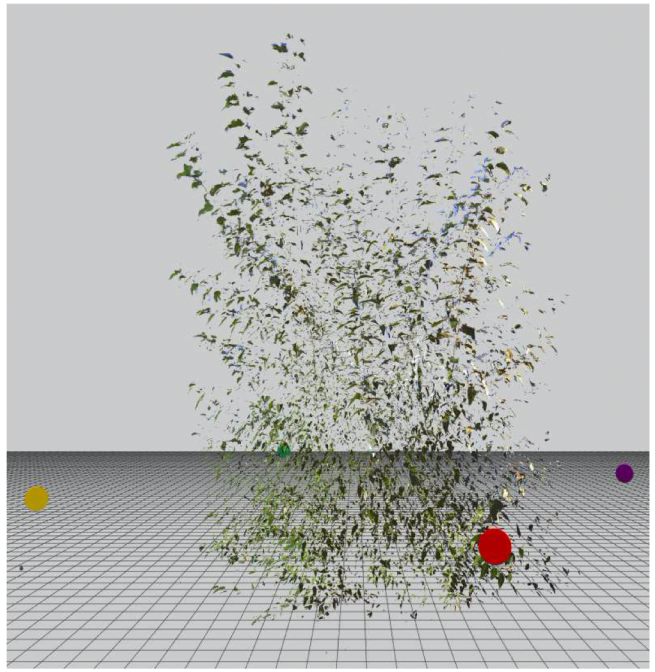


(Gregoire et al., 2017)

Foliage triangulation from Lidar

- Filtered triangulation of foliage (Bailey et al., 2017)





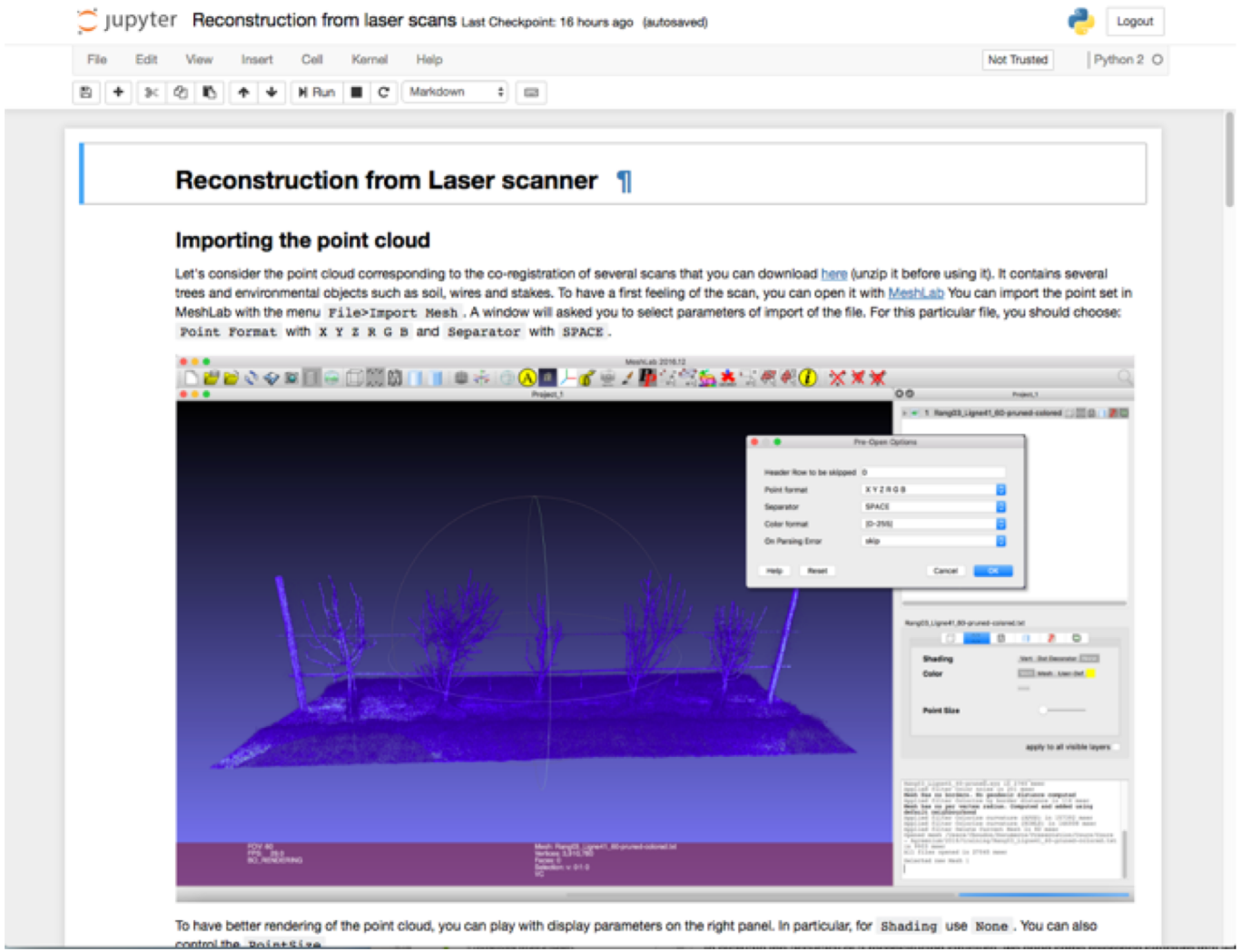
Conclusion

- A rapidly improving field.
  - New acquisition devices
  - New processing techniques (deep learning).
- Testing different protocols and devices

	Lidar	Digitizing	Photogrammetry
Cost	>30 k€	~ 8k€	~ 8k€
Range	~100 m	~ m	~ 100 m
Precision	++	+++	+
Software	In development	Operational	In Development /Operational

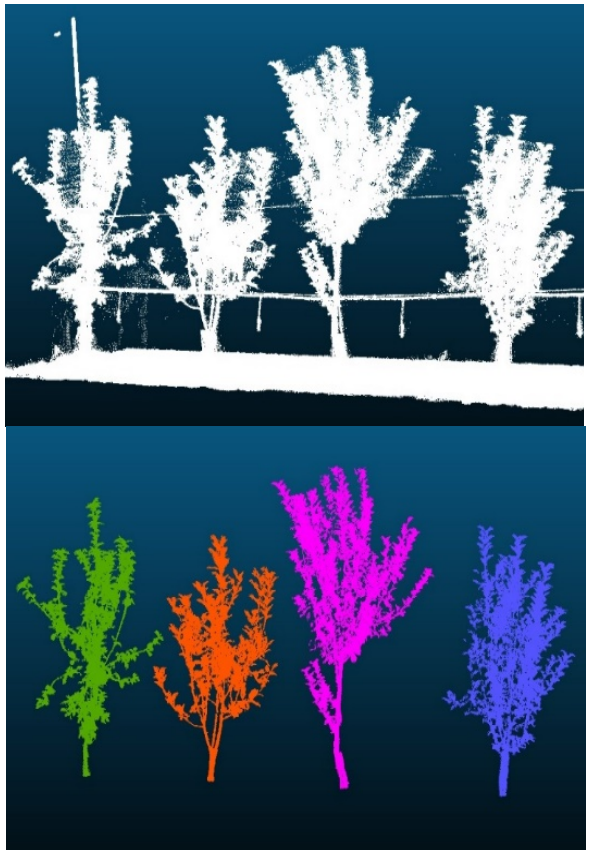
Training

https://github.com/openalea-training/hbma312_training/blob/master/laserreconstruction/Reconstruction%20from%20laser%20scans.ipynb

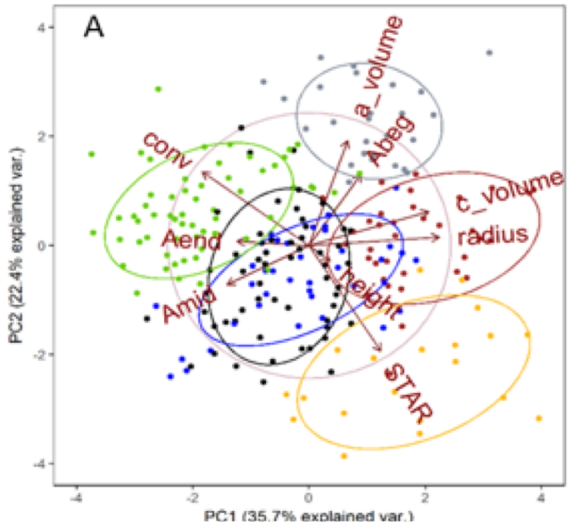


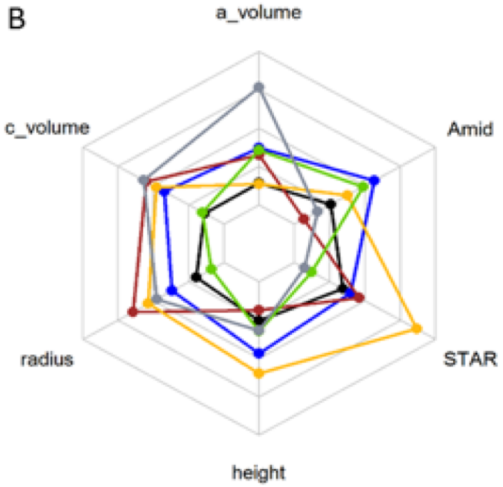
Application for the classification of genotypes into morphotypes

- Scan of a core collection

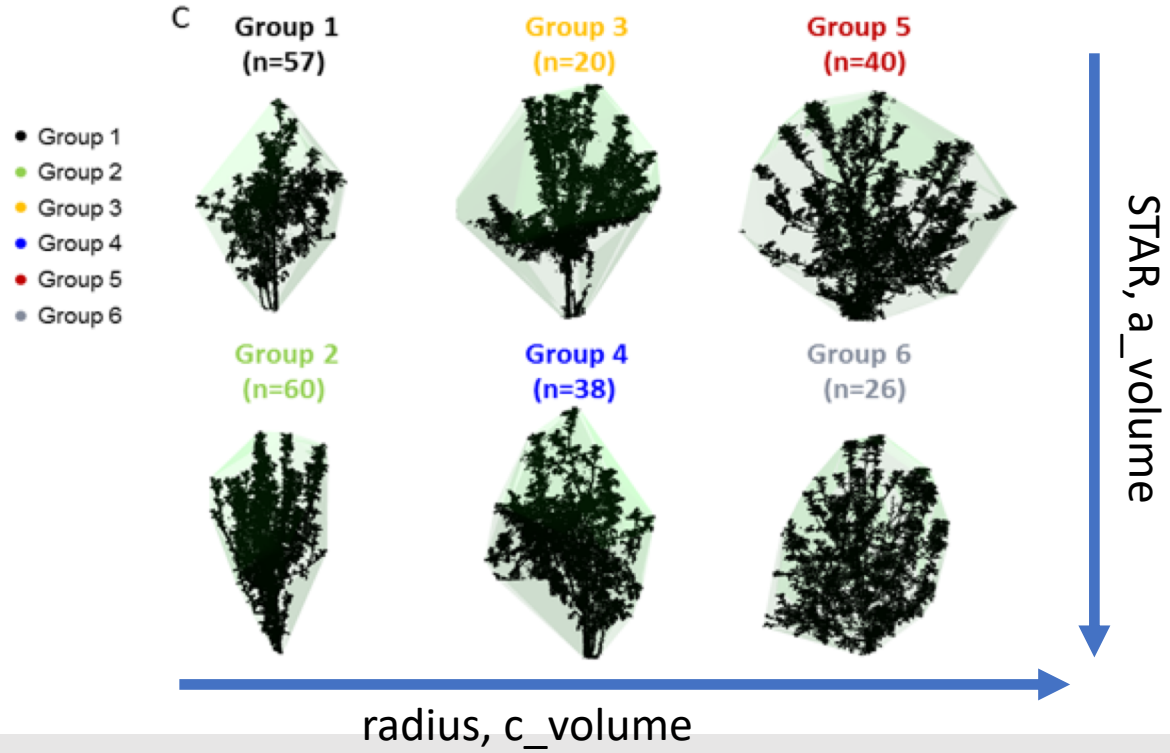


- PCA





- Clustering



- Traits estimation
  - Tree radius R and height H
  - Convex volume (c_volume)
  - Alpha volume (a_volume)
  - Convexity (a_volume/c_volume)

Cf TD

(Pallas et al., 2018)

Thank you