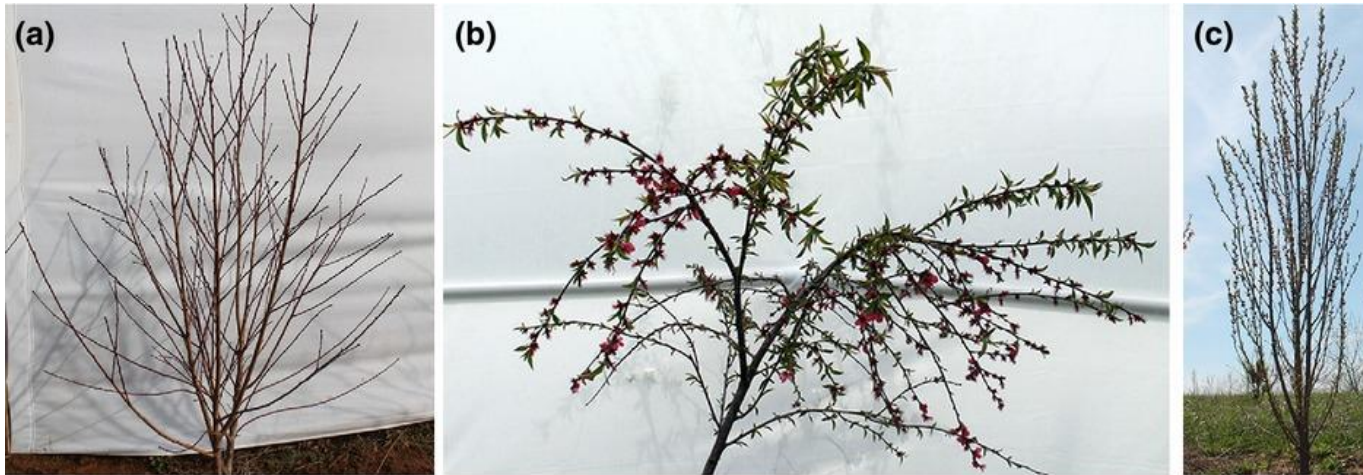


High-throughput phenotyping of fruit tree development, light interception and water-use related traits: a case study on apple tree

Evelyne Costes
UMR AGAP, Montpellier

Tree architecture is genetically highly variable in fruit species

Peach tree



Monet (1983); Scorza (1984); Scorza 1984; Bassi et al., 1992) photos from Hollender and Dardick (2014)

Apple tree

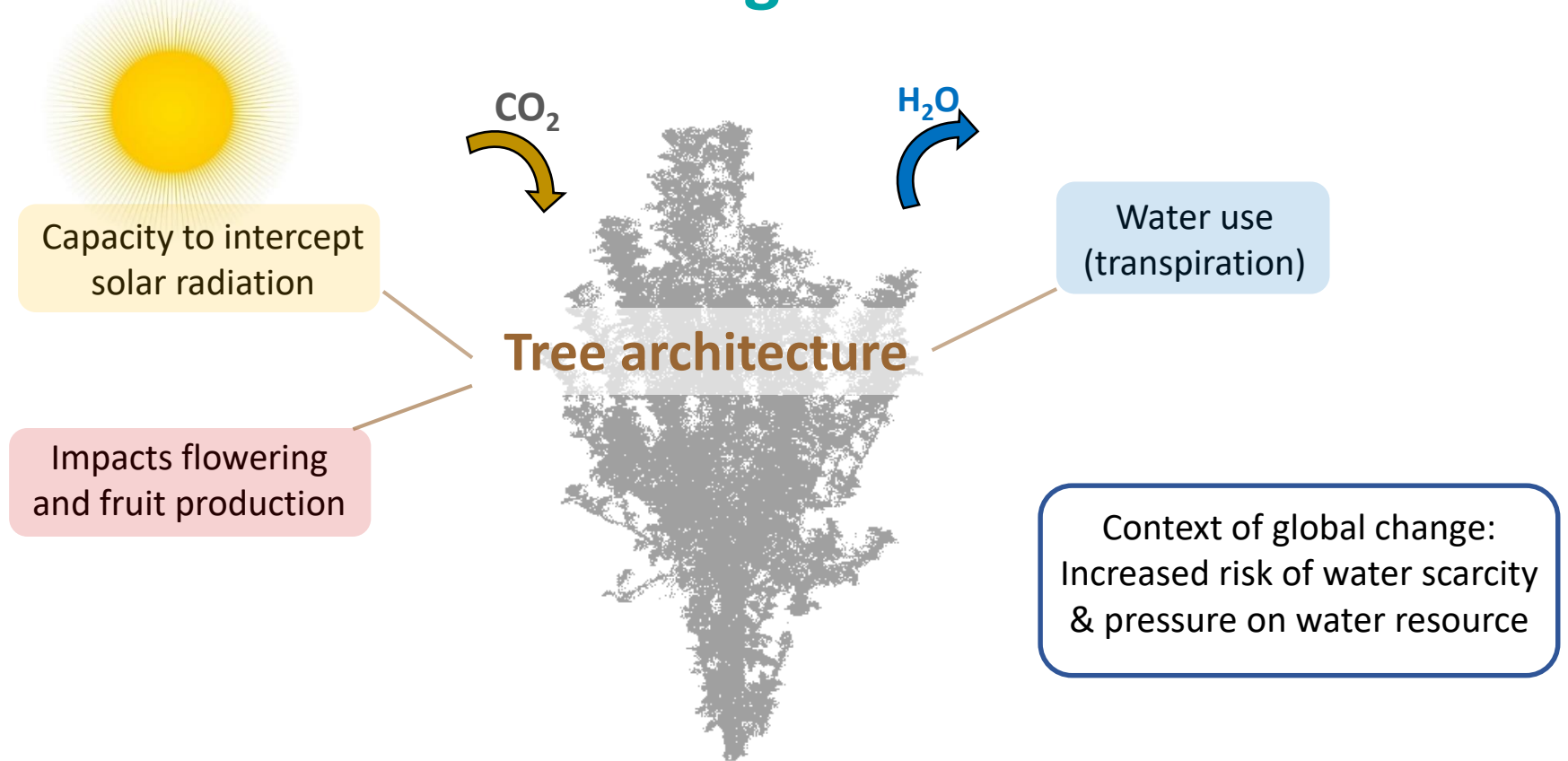


© C. Costes, INRAe

Lespinasse, (1992); Lauri and Lespinasse, (1993); Forshey and Elfving, (1989)

Both tree topology and geometry are varying depending on the variety

Tree architecture is a key feature for fruit production in the face of climate change



In silico modeling achieved optimal combinations of architectural and functional traits

➤ Resource use efficiencies are important targets, not accounted for in breeding programs

- Their genetic control has rarely been investigated jointly with architecture
- Major bottleneck : phenotyping these traits in field conditions on adult trees

Phenotyping: overall strategy

1. High-Throughput measurements

Tree architecture, form and vigour
Tree photosynthetic activity and transpiration

Coupel-Ledru et al., 2019

2. Validation

1. **Subset of genotypes:**
Fine, *in planta* measurements

3. Genetics

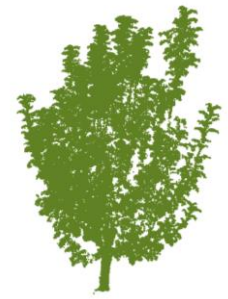
Genetic variability
GWAS

Coupel-Ledru et al., 2022

T-LiDAR : Architecture (geometry-topology)
Nb of axes, tree volume, etc.



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Airborne imaging:

- Multispectral imagery (Vegetation indices)
 - Thermal images (Stress indices)
- Response of the canopy water loss to drought



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Production and other variables:

- Yield (fruit number & harvest weight)
- Trunk cross sectional area

Experimental design

INRA Mauguio : Diascope Experimental Unit

(43°36'N, 3°58'E, 10m a.s.l.)

- Apple tree French core collection (Lassois et al., 2015)
- 241 genotypes x 4 replicates (same M9 rootstock)



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Mediterranean climate (dry summer)
Soil : limited water holding capacity:
irrigation withdrawal → water stress

- Plot 1.2 ha
- 10 rows (ca. 200m)
- Plantation spring 2014
- Micro-irrigation, individual emitters
- Row weeding ; grassed inter-rows
- No pruning, fruitlet thinning,
- Conventional spraying
- 5x2m spacing, compatible with architecture characterization

Micrometeorology:

Global & PAR
radiation,

Air temperature & RH,
Wind speed &
direction

Soil water status:

Sentek capacitive probes (0-90cm)

+Tensiometers (-30 and -60cm)

For 14 tree locations

2 different water regimes during summer

- WW = well irrigated
- WD = water deficit
- WW / WD trees, facing each other (2 pairs)

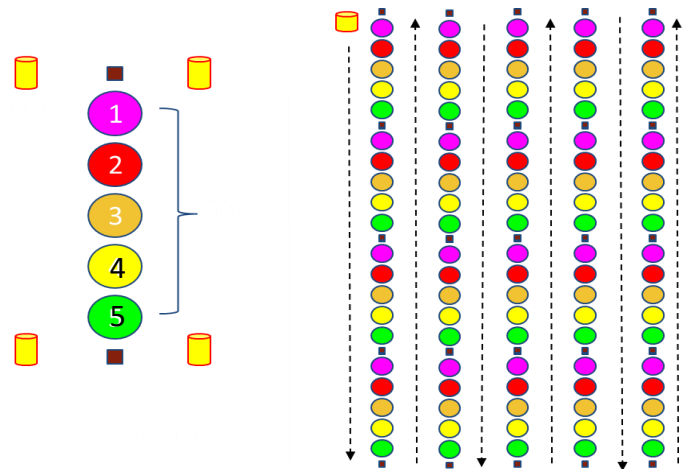
© M. Delalande, INRAe

Using T-LiDAR to assess tree architectural variability

1. Field acquisition

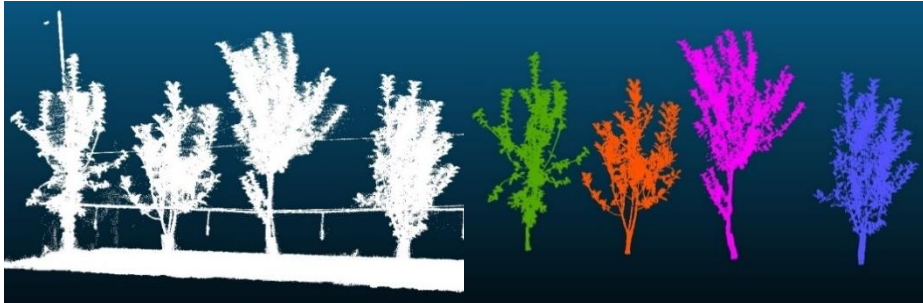
Two campaigns in summer and winter 2017

250 scans
Scan resolution 0.06 (6mm at 10m)
Acquisition duration: 30'/scan
5 days for 998 trees



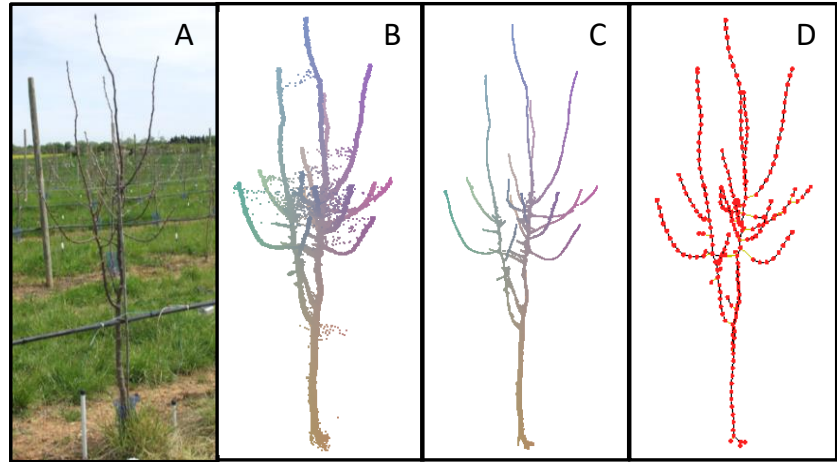
2. Data post-processing (filtering, topological reconstruction, tree segmentation)

Tree segmentation



ComputeTree and RiscanPro

Filtering – contraction Reconstruction

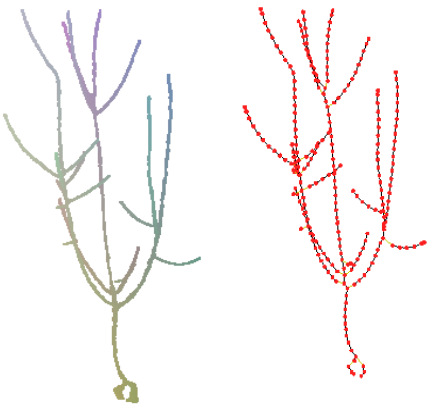
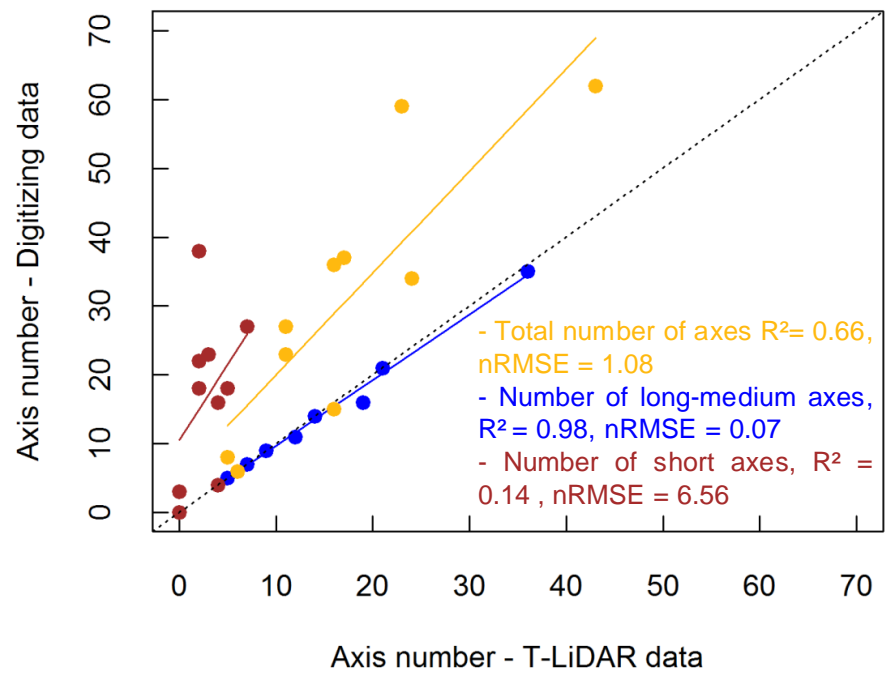


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Architectural traits estimated from T-Lidar scans (winter)

Topological variables:

Number of axes according to their types – T-Lidar vs digitizing data



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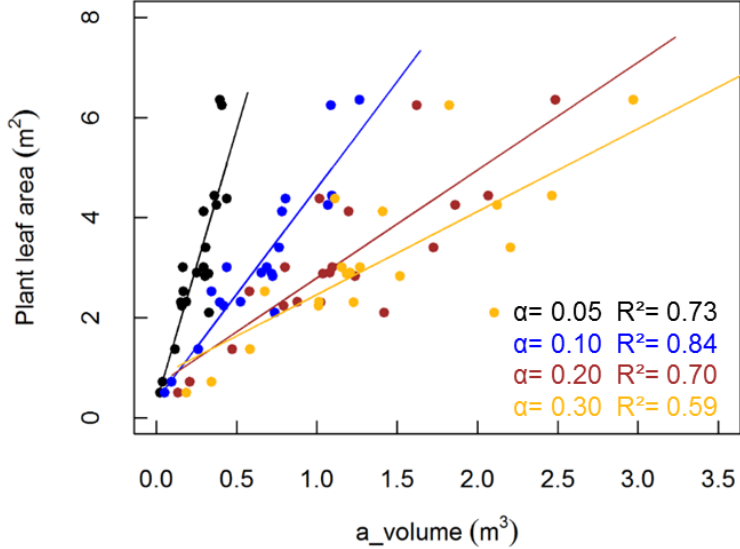
Complete dataset

Variables	Mean value (Digitizing)	R^2
Total nb of axes	36.3	0.66
Nb of long + medium axes	22.7	0.98
Nb of short axes	13.6	0.14
Cumulative axis length	7.2m	0.99
Cumulative length of long & medium axes	6.6m	0.99
Cumulative length of short axes	0.6m	0.10

Architectural traits estimated from T-Lidar scans (summer)

Geometrical variables

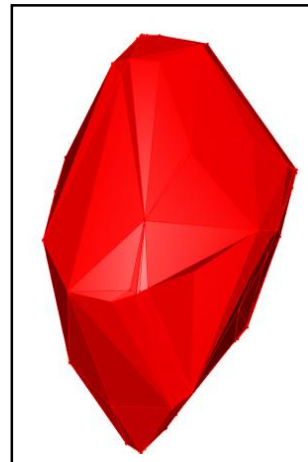
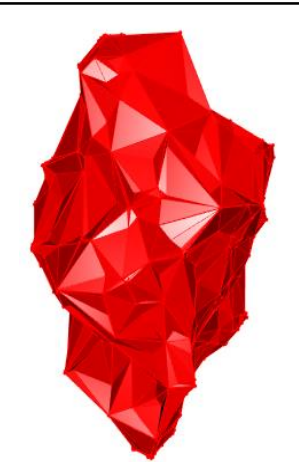
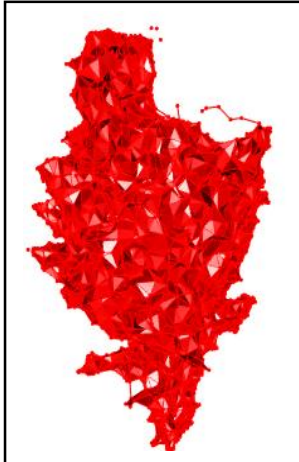
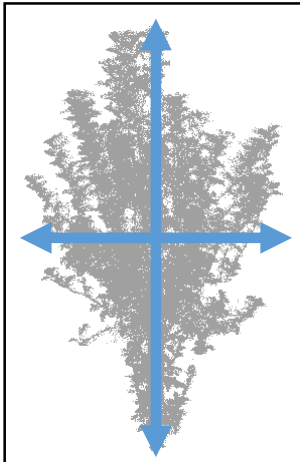
- Tree radius R
- Tree height H
- Convex volume (c_volume)
- Alpha volume (a_volume)
- Convexity (a_volume/c_volume)



$\alpha = 0.05$

$\alpha = 0.20$

$\alpha = 0.40$



Alpha hulls

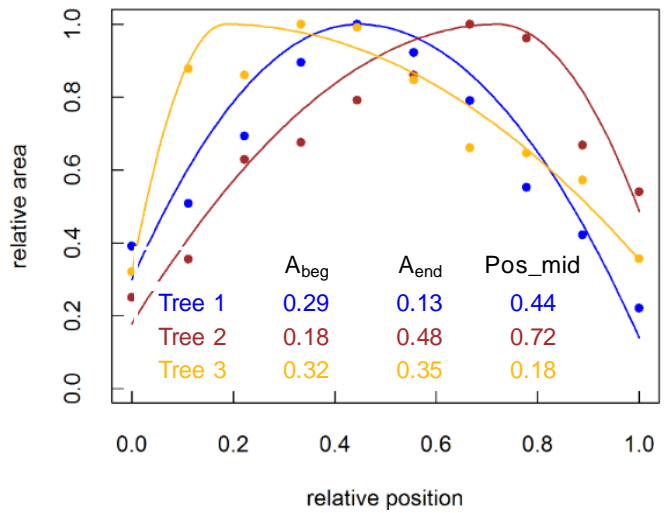
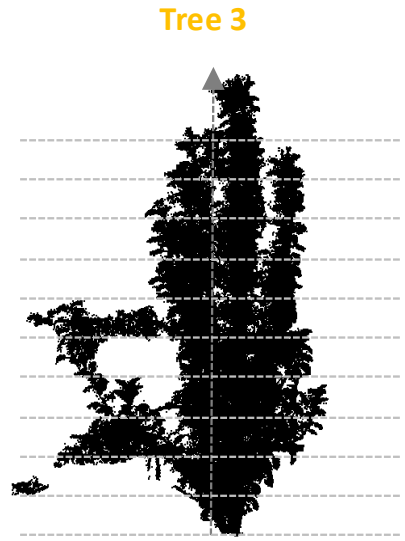
Convex hull

Architectural traits estimated from T-Lidar scans (summer)

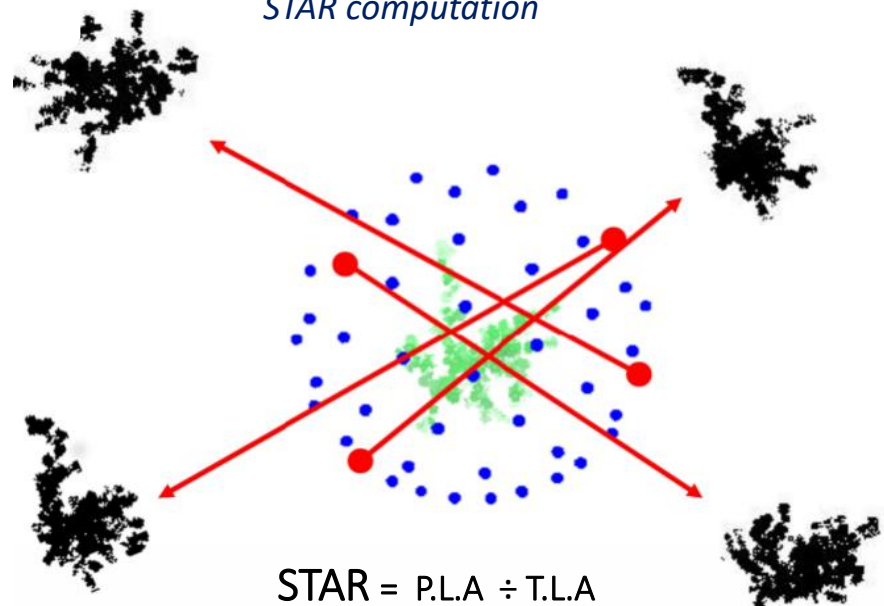
Computation of leaf area profile parameters (3 trees)

Geometrical variables

- Leaf area profile
- STAR (Silhouette to total leaf Area Ratio)



STAR computation



From Da Silva et al. 2014

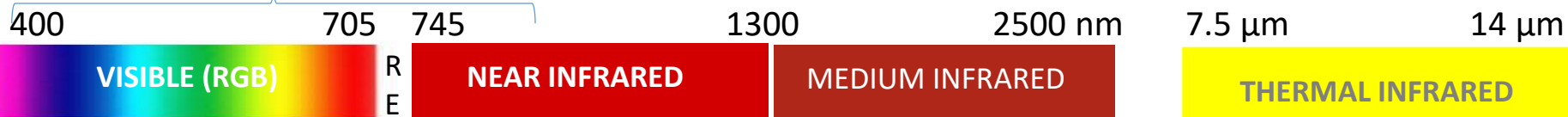
High-resolution multispectral and thermal-IR imagery



AirPhen® 3 / HiPhen



Flir® Tau-2



Pigment Absorption

- Chlorophyll
- Carotenoids (Xanthophyll)
- ...
- Brown pigments
- **Fluorescence**

Molecule Absorption

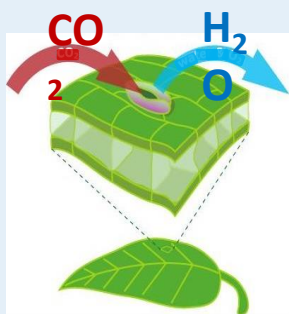
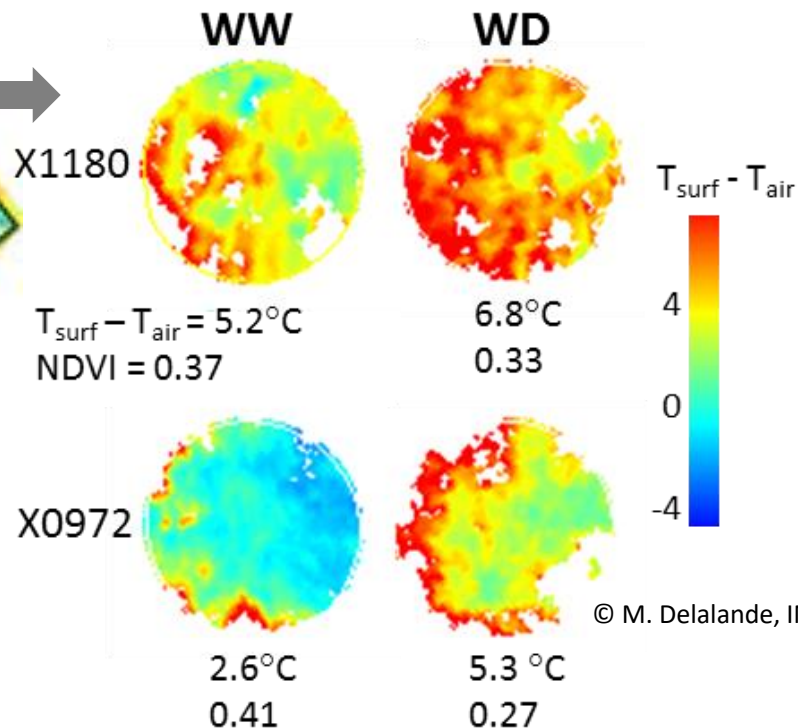
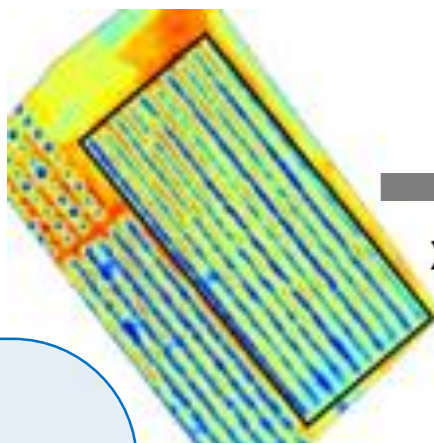
- Water
- Organic compounds
 - Proteins
 - Cellulose
 - Lignin
 - ...

Radiation emission

- Temperature
- Emissivity

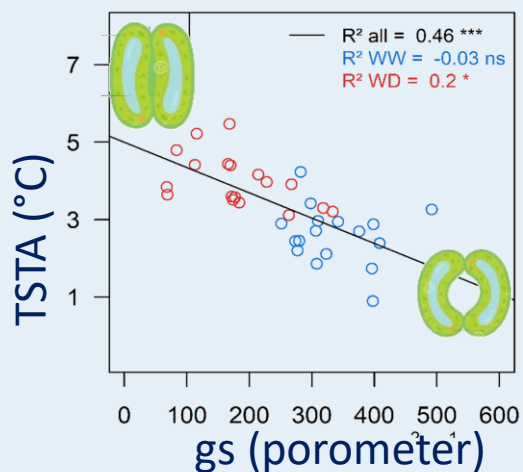
Vegetation Indices (VI) & Stress indices	Biological features	Spectral bands							References	
		450 nm	532 nm	568 nm	675 nm	730 nm	750 nm	850 nm		7.5-14μm
NDVI	Green Area Index (GAI)				X			X		Rouse et al., 1974
GNDVI	GAI (+ chlorophyll)			X				X		Gitelson et al., 1996
MCARI	GAI		X		X	X				Daughtry et al., 2000
MCARI_2	GAI (-chl.), LAI and FIPAR		X		X			X		Haboudane et al., 2004
PRI	Xanthophyll cycle, Photosystem II efficiency		X	X						Gamon et al., 1992
Ts-Ta; CWSI; WDI	Water stress				X			X	X	Maes & Steppe, 2012; Idso et al., 1981; Moran et al., 1994

Thermal-IR imaging



Leaf cooling

Relation with g_s on a single leaf



Computation of mean pixels values per individual tree

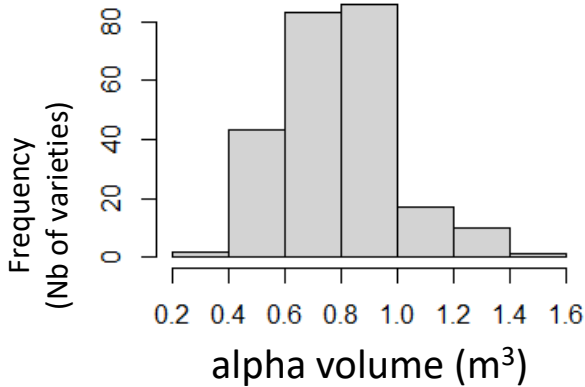
$TSTA = T_{surf} - T_{air} =$ canopy surface temperature

Some results on traits retrieved from T-LIDAR scanner and multispectral imaging

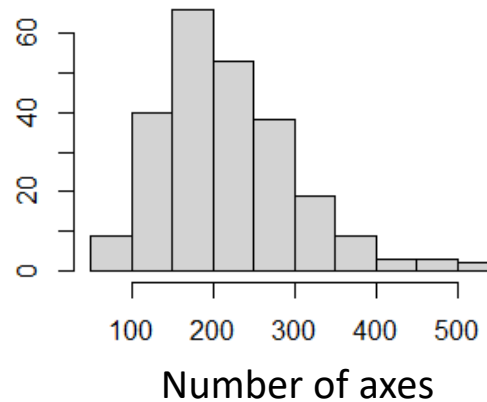
Coupel-Ledru et al., 2022

A strong genotypic variability on all traits related to **architecture** and **light interception**, and **vegetation indices**

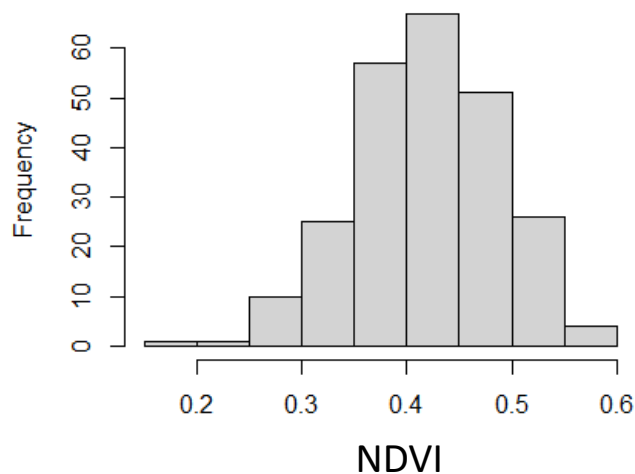
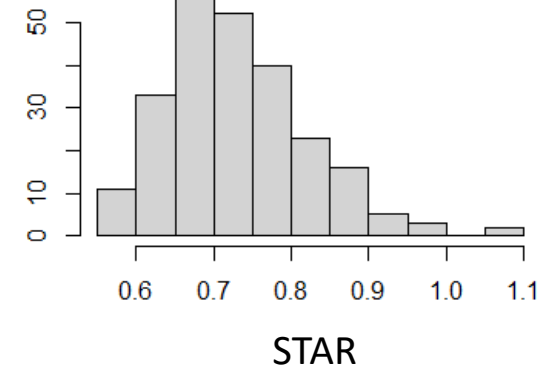
Leaf area



Shoot development



Light interception efficiency (self-shading)



No effect of WD on these traits
(or very light)

*Likely due to the short duration (1 month)
and period (July) of WD application*

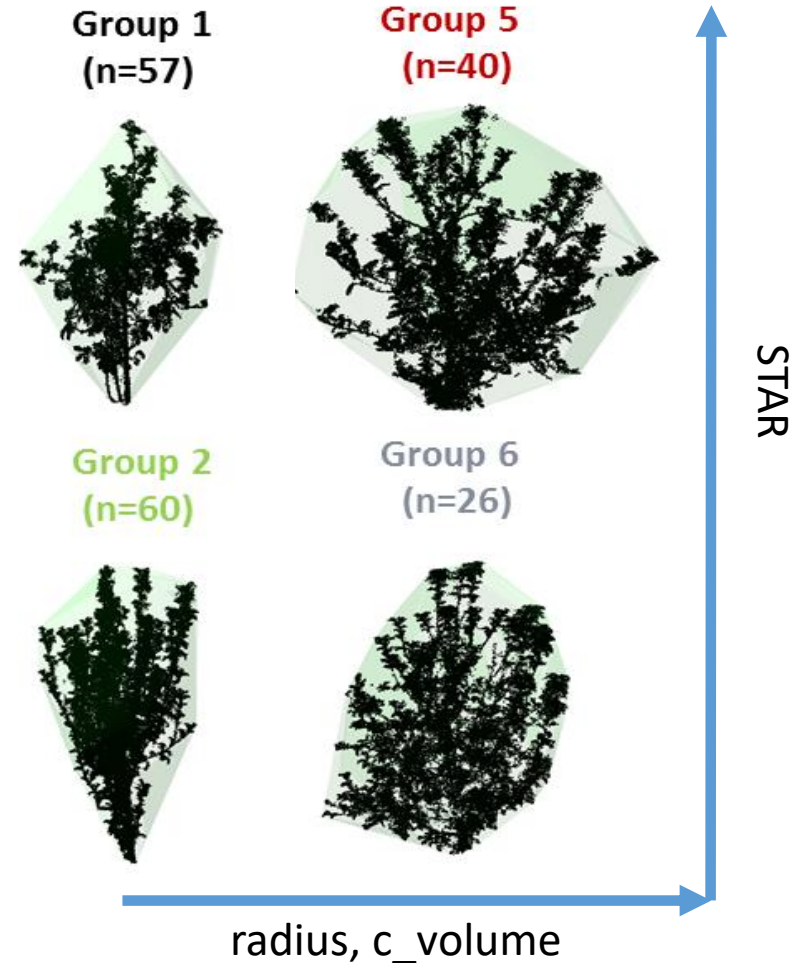
A strong genotypic variability on all traits related to architecture and light interception, and vegetation indices

Heritability of tree traits

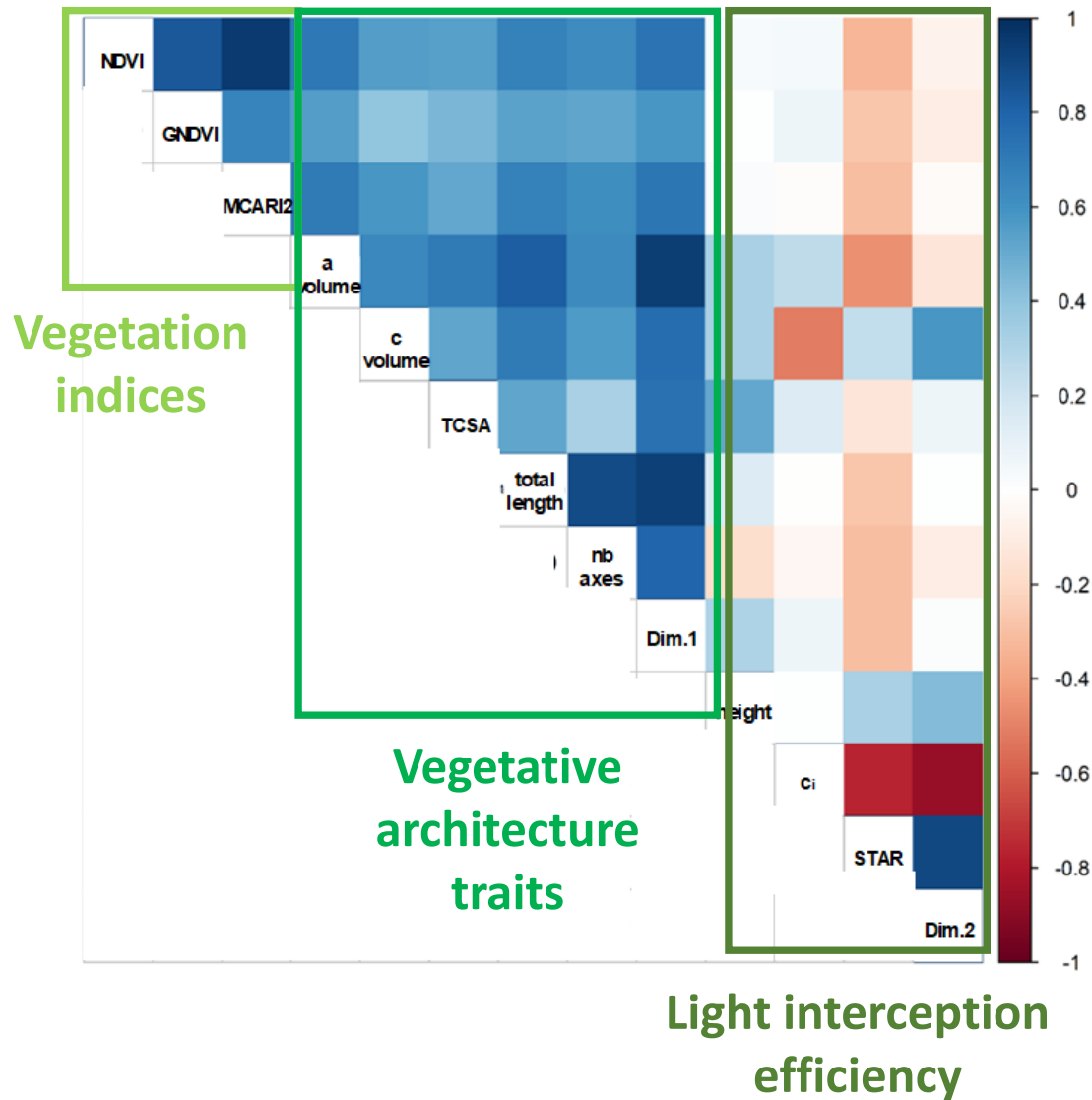
Mixed effect model $Y = \mu + G + T + X + \varepsilon$

μ : intercept, G : genotypic effect (random), T : treatment effect (fixed), X possible other fixed effect (row, date...)

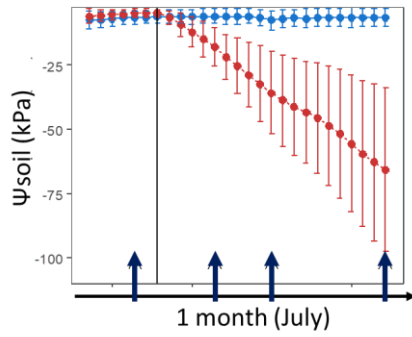
Measurement type	Trait	Broad sense H ²
Multi-spectral imagery	NDVI	0.94
	GNDVI	0.94
	MCARI2	0.92
T-LiDAR data	c_volume	0.82
	a_volume	0.77
	c _i	0.86
	STAR	0.79
	height	0.81
	total_length	0.80
	nb_axes	0.83



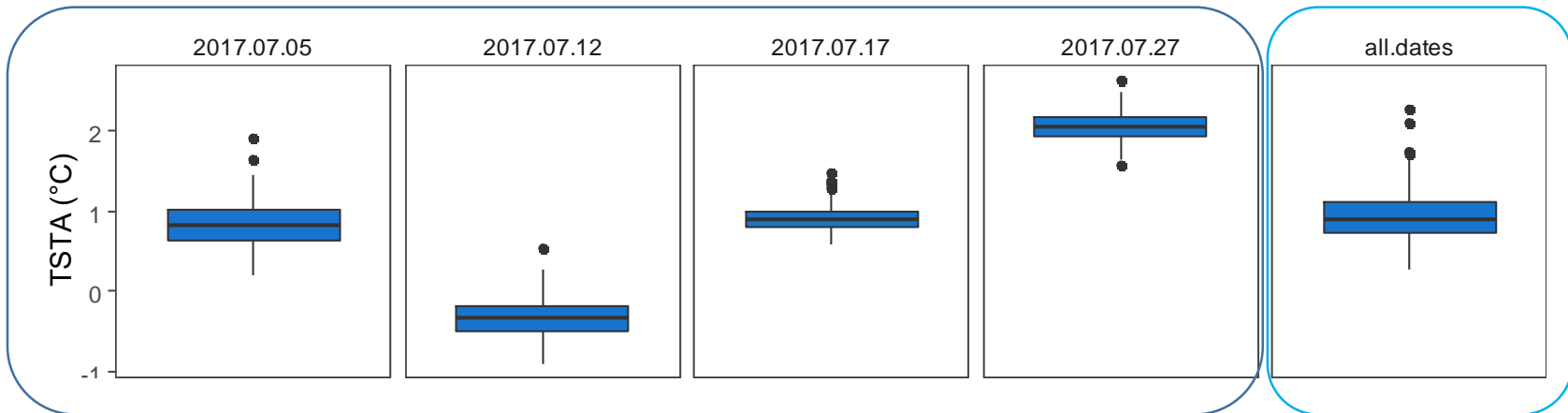
Two different groups of traits within the collection



Genotype-dependent control of canopy temperature in WW conditions

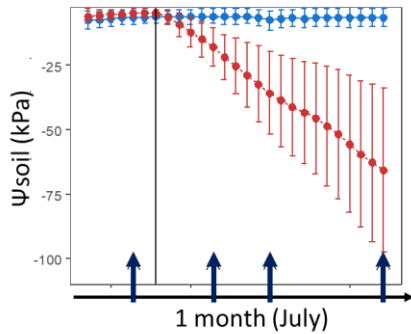


TS-TA for well-watered trees:
Significant genotypic effect but variability across dates
Likely due to atmospheric variations



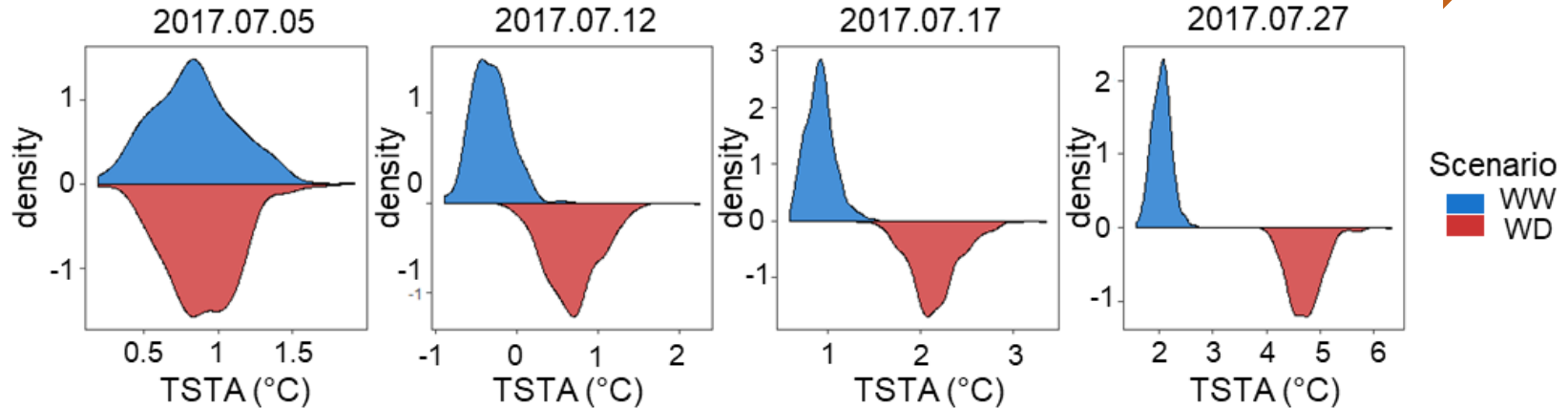
⇒ Calculation of one WW genotypic value accounting for date effect
⇒ $H^2=0.76$

Large genotypic variations in the response of canopy surface temperature to intensifying soil drying

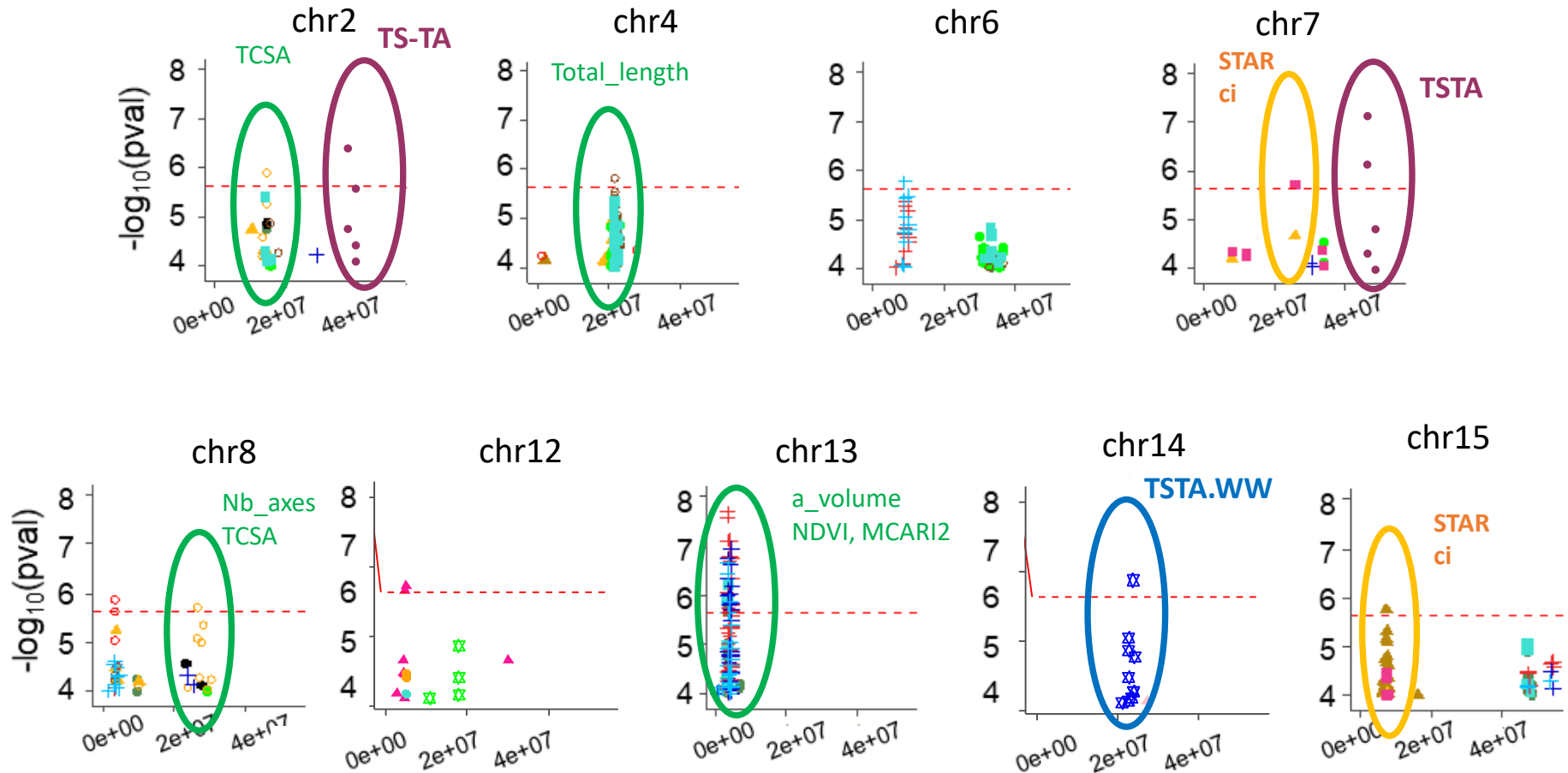


TS-TA for **WD trees** : $H^2 = 0.4-0.6$

Soil drying



Different genomic regions control canopy temperature, vegetative architecture or light interception efficiency



Multiple allelic combinations exist within the collection for the three groups of traits \Leftrightarrow **Possibilities of selecting independently for architecture, light interception efficiency and water loss**

Take home messages

- The simultaneous assessment of canopy vegetative development and canopy functioning revealed to be efficient to
 1. Classify trees according to their global shape
 2. Assess the relevance of indices derived from scans and airborne imagery as proxies for tree architecture and functioning
 3. Capture the genetic variability of those traits in an apple tree core collection
- GWAS revealed that multiple allelic combinations exist within the collection for the three groups of traits
 - ↔ It will be possible to select independently for **architecture**, **light interception efficiency** and **water loss**
 - ↔ Find adequate combinations depending on the climatic conditions?
- How to define / evaluate the water-use efficiency on a medium to long term for perennial crops ?

Acknowledgements



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Emma Carrié (Master student)

Olivier Simler (Master student)



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Diascope : INRAe experimental unit

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UMR TETIS

Laurent Albrech

UMR IRHS

Hélène Muranty

Charles-Eric Durel

Founders

INRAe



Thank you for your attention

Some related literature:

Coupel-Ledru et al. 2022. Tree architecture, light interception and water use related traits are controlled by different genomic regions in an apple tree core collection. *New Phytologist* 234: 209-226 <https://doi.org/10.1111/nph.17960>

Coupel-Ledru A. et al. 2019. Multi-scale high-throughput phenotyping of apple architectural and functional traits in orchard reveals genotypic variability under contrasted watering regimes. *Horticultural Research*, 6(1): 52.
<https://doi.org/10.1038/s41438-019-0137-3>

Pallas et al. 2020. Assessing T-LiDAR technology for high throughput phenotyping apple tree topological and architectural traits. *Acta Hortic.* 1281: 625:632

Delalande et al. 2018. Do multispectral and thermal IR high-resolution UAS-borne imagery help in phenotyping the tree response to water stress at field? Case studies in apple diversity population and varietal assays. XXX International Horticultural Congress IHC2018: VII Conference on Landscape and Urban Horticulture, *Acta Horticulturae* 1279.

Gómez-Candón et al. 2017. Contribution of high-resolution multispectral and thermal-infrared airborne imagery to assess the behavior of fruit trees facing water stress: proof of the concept and first results in an apple variety field trial. EFITA WCCA 2017 Conference, Montpellier SupAgro, Montpellier, France, July 2nd-6th, 2017.
110. <http://CIGRProceedings.org>

Boudon et al. 2014. Quantitative assessment of automatic reconstructions of branching systems obtained from laser scanning. *Annals of Botany* 114 (4), 853-862.