Are pavements a major cause of tree decline?

Alessio Fini1*, Sebastien Comin1, Irene Vigevani2,3, Denise Corsini1, Irene Pagliarini4, Alessandra Turrini4, Monica Agnolucci4, Francesco Ferrini2, Piero Frangi5

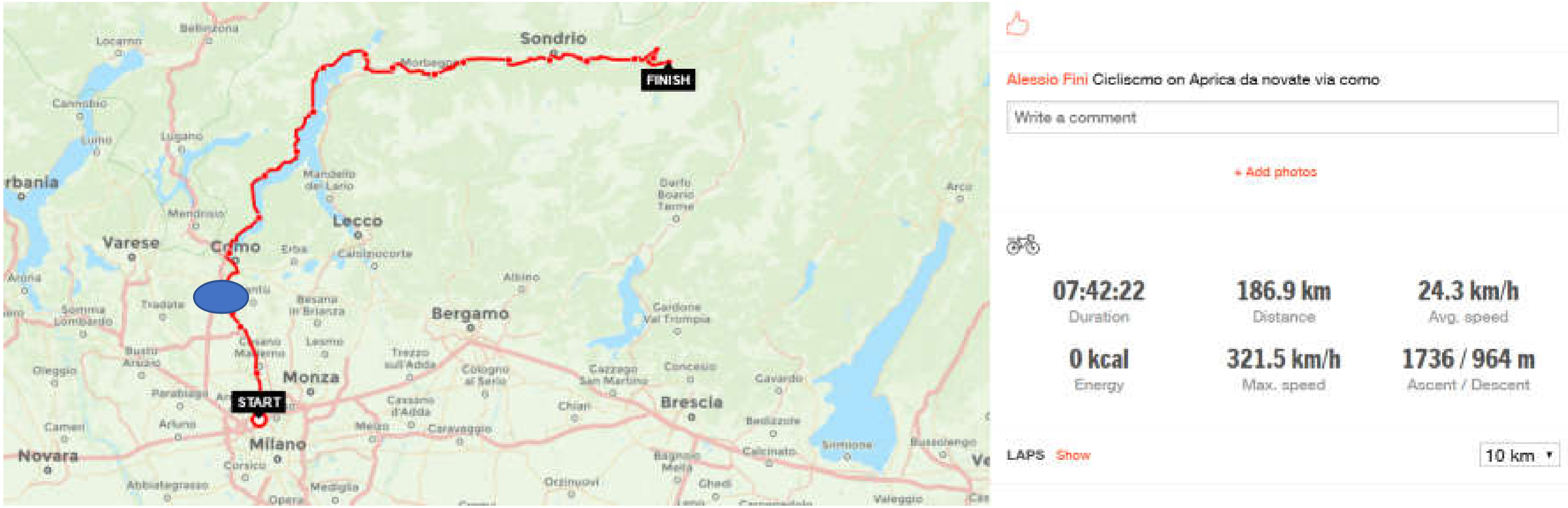
1 Department of Agricultural and Environmental Sciences – Landscape, Production, Agroenergy, University of Milan, via Celoria 2, 20133, Milano, Italy; 2 Department of Agriculture, Food, Environment and Forestry, University of Florence, Viale delle Idee, 30, 50019, Sesto Fiorentino, FI, Italy; 3 Department of Sciences, Technologies and Society, University School for Advanced Studies IUSS Pavia, Piazza della Vittoria, 15, 27100, Pavia, PV, Italy; 4 Department of Agriculture, Food and Environment, University of Pisa, Via del Borghetto 80, 56124 Pisa, Italy; 5 Fondazione Minoprio, viale Raimondi 54, 22070 Vertemate con Minoprio, Italy.

It was August 5th, 2011, ISA conference in Sydney just over. Everything was ready for a cycling holiday around Italy






The first stage stopped for a while in Vertemate con Minoprio (after just 20 km).
Something was going to start there..

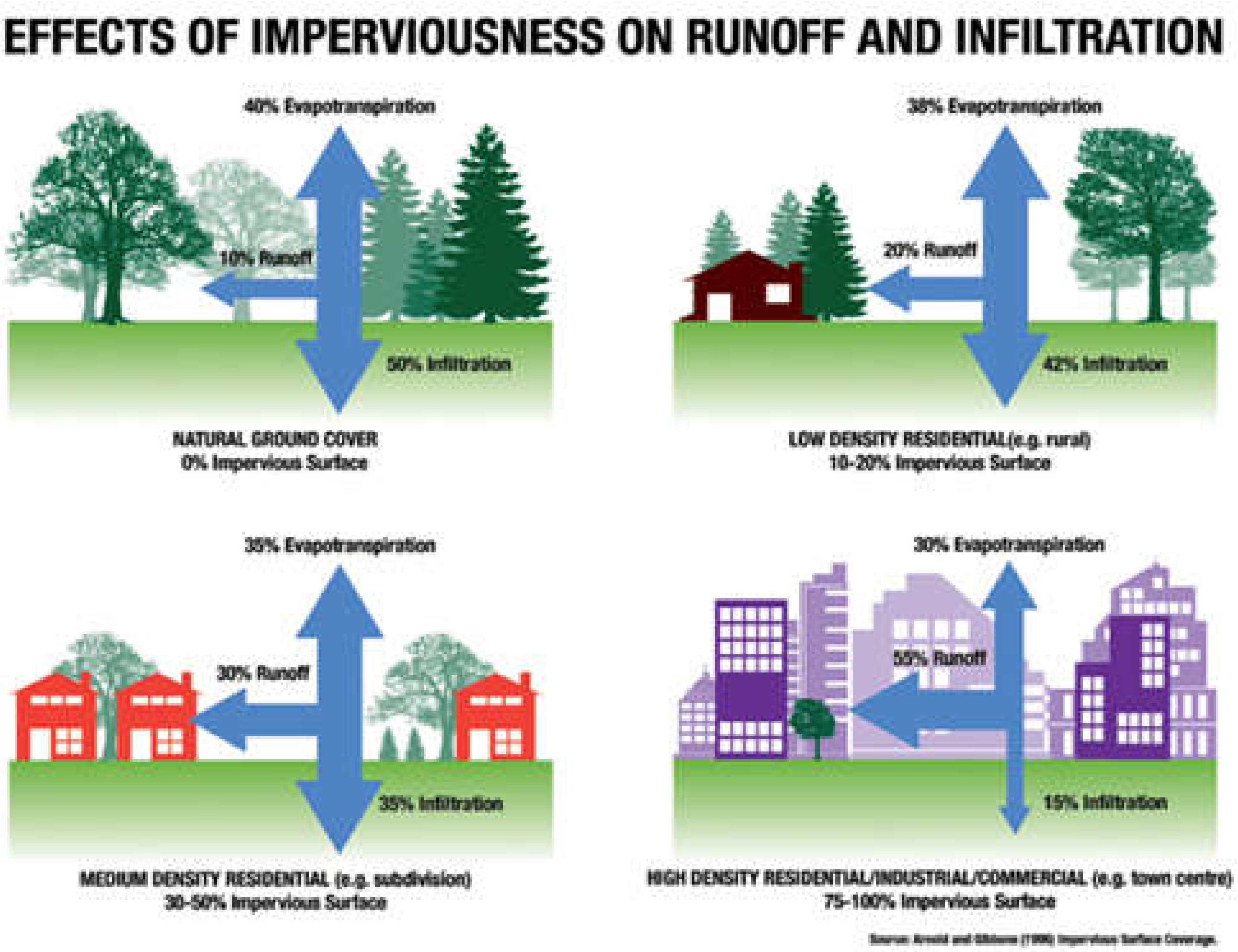


Regione Lombardia

Regione Lombardia (project METAVERDE) funded a research to **evaluate the effects of soil sealing** and find possible mitigation strategies
In an August meeting, the experimental field was designed.
That, indeed, yielded the cyclists a storm while ascending the final slope

Soil sealing, “the covering of soil by buildings, constructions, and layers of completely or partly impermeable artificial materials” is the most pervasive form of land take and it is essentially an irreversible process (*Alberti, 2005*)

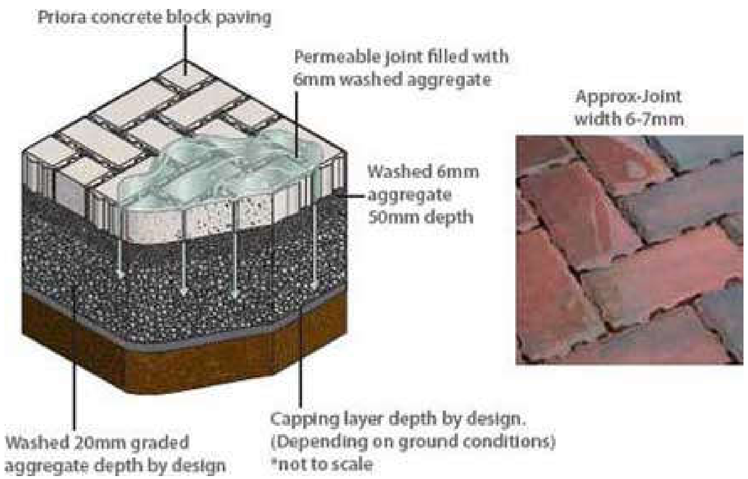
In Italy, about 2 m^2 soil are sealed every second (*ISPRA, 2022*).



The understanding that extensive soil sealing increases runoff and reduces infiltration has lead to:

1- the idea that **pavements may induce water stress in trees**

2- the development of **alternative pavements** to reduce runoff



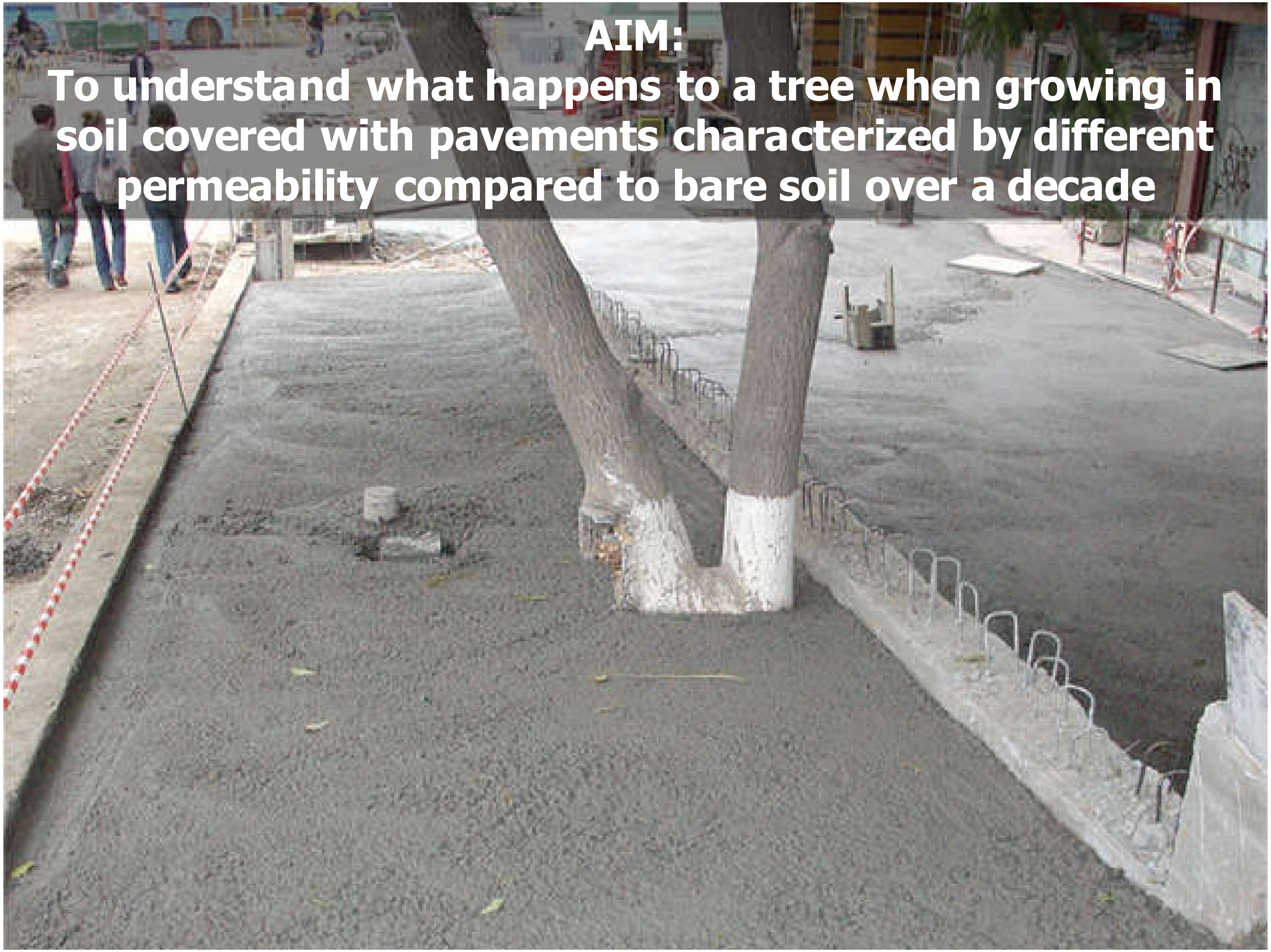
livinglandscapes.uk.com

POROUS PAVEMENTS:

The pavements itself is permeable to water across its entire structure

PERMEABLE PAVEMENTS:

Pavements made by impervious modular elements, but voids between elements allow water infiltration


AIM:
To understand what happens to a tree when growing in soil covered with pavements characterized by different permeability compared to bare soil over a decade

Soon after, the construction begun

Pouring down the porous pavement

Barriers buried down to 70 cm to separate plots

Cilinders for soil respiration measurement

1 m2 unpaved planting pit

Concrete sub-grade in the “impermeable” treatment

Four soil treatments were imposed

Impermeable design: asphalt on a concrete sub-grade

Permeable desing: curb on a crushed rock sub-grade

Porous desing: epoxy resin + even-graded inert on a crushed rock sub-grade

Control: unpaved soil (chemical weeding used for weed control)

Soil traits before paving

Soil trait	Value
Gravel	170 g/kg DM
Sand	28,2%
Silt	61,4%
Clay	10,4%
pH	7,6
Organic Matter	2,1%
Lime (reactive)	< 1%
Cation Exchange Capacity	13,2 meq/100 g DM
N (total)	1,4 g/kg DM
P (available)	19 mg/kg DM
K (exchangeable)	0,2 meq/100 g DM

Soil is a slightly alkaline sandy silt soil with low lime and an average organic matter content

Two shade tree species were planted in March 2012

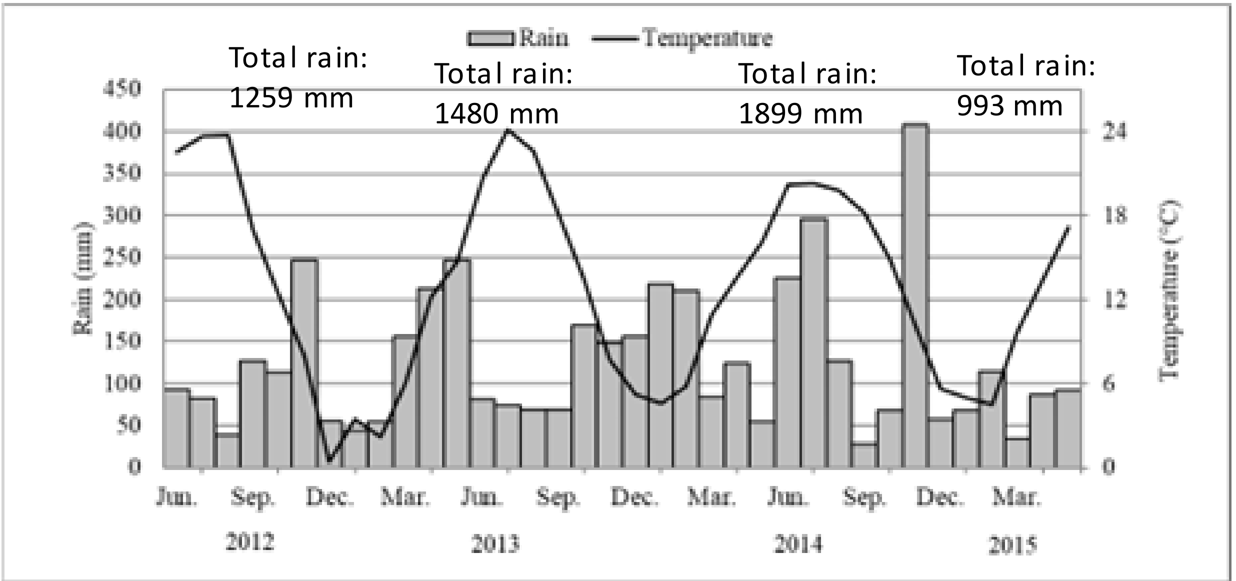
- *Celtis australis* L. - hackberry
- *Fraxinus ornus* L. – manna ash

- 24 B&B plants per species (14-16 cm circumference; 2'' caliper) were planted according to a randomized block design with 6 blocks

- <u>*Celtis*</u> is a **coarse-rooted isohydric** water-spending species: it bases its tolerance to drought on the **capacity to explore deeply the soil in search of water, and to conduct quickly to leaves to compensate for transpirational losses**. Photosynthesis generally decreases more than pre-dawn water potential during drought, but neither are large decreases

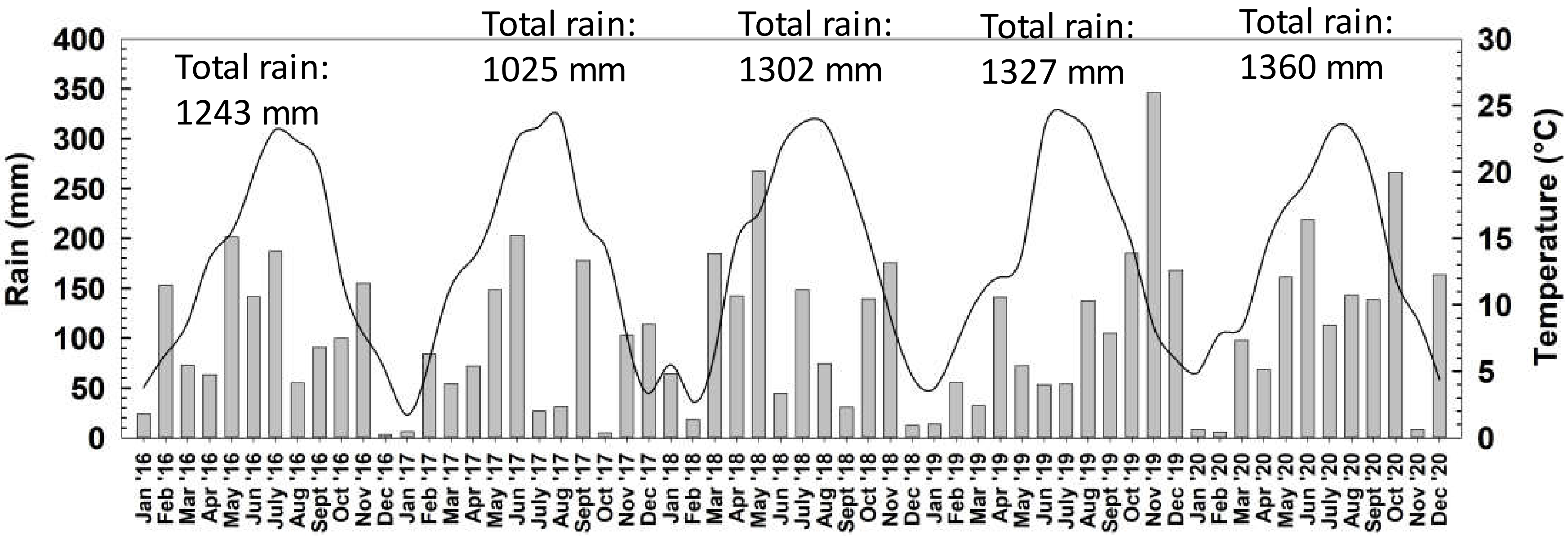
- <u>*Fraxinus*</u> is a **fibrous rooted anisohydric** species: it tolerates drought accumulating compatible solutes in leaves, to **adjust osmotically** and increase its capacity to extract water from a given soil volume

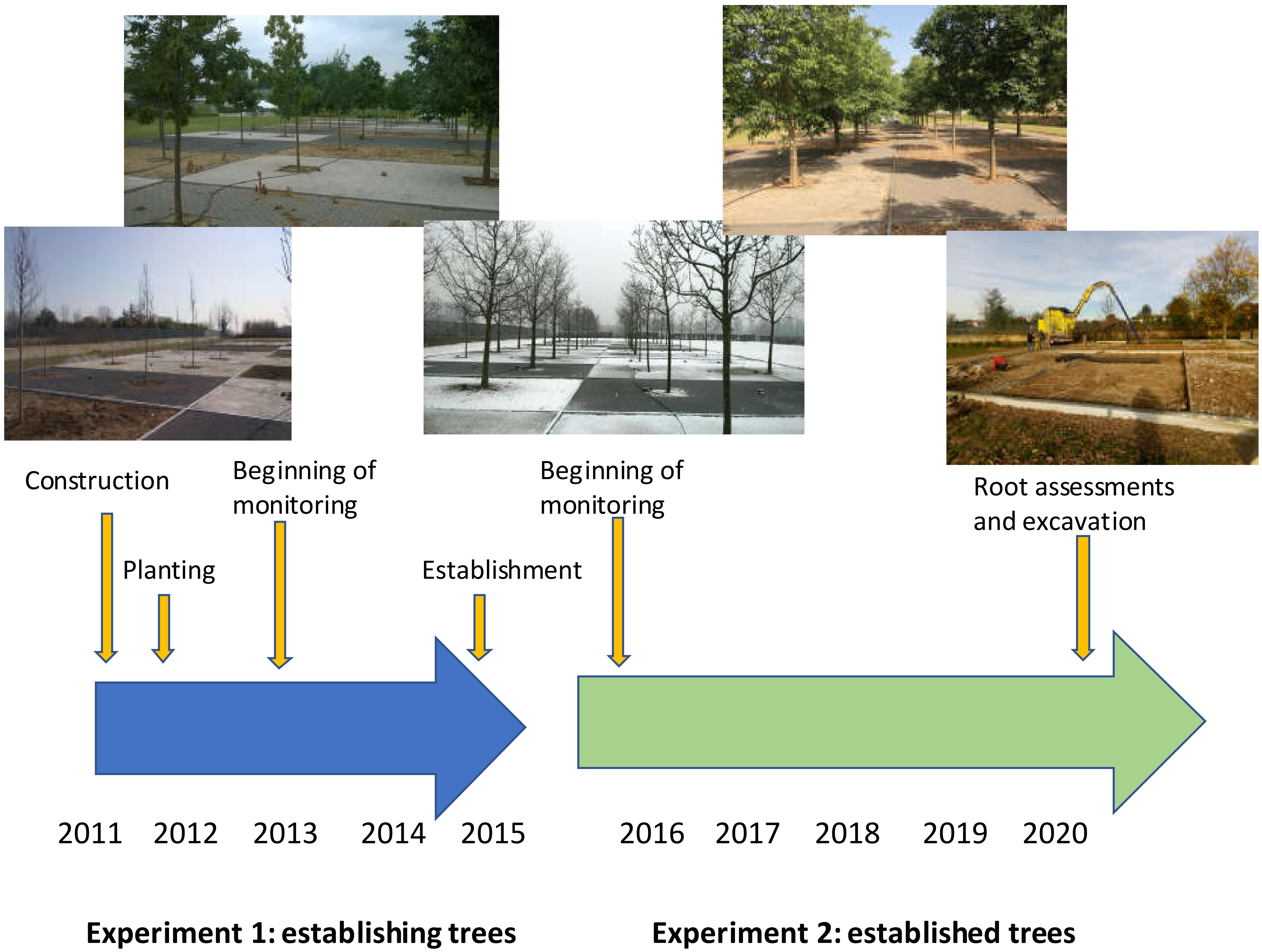
During establishment

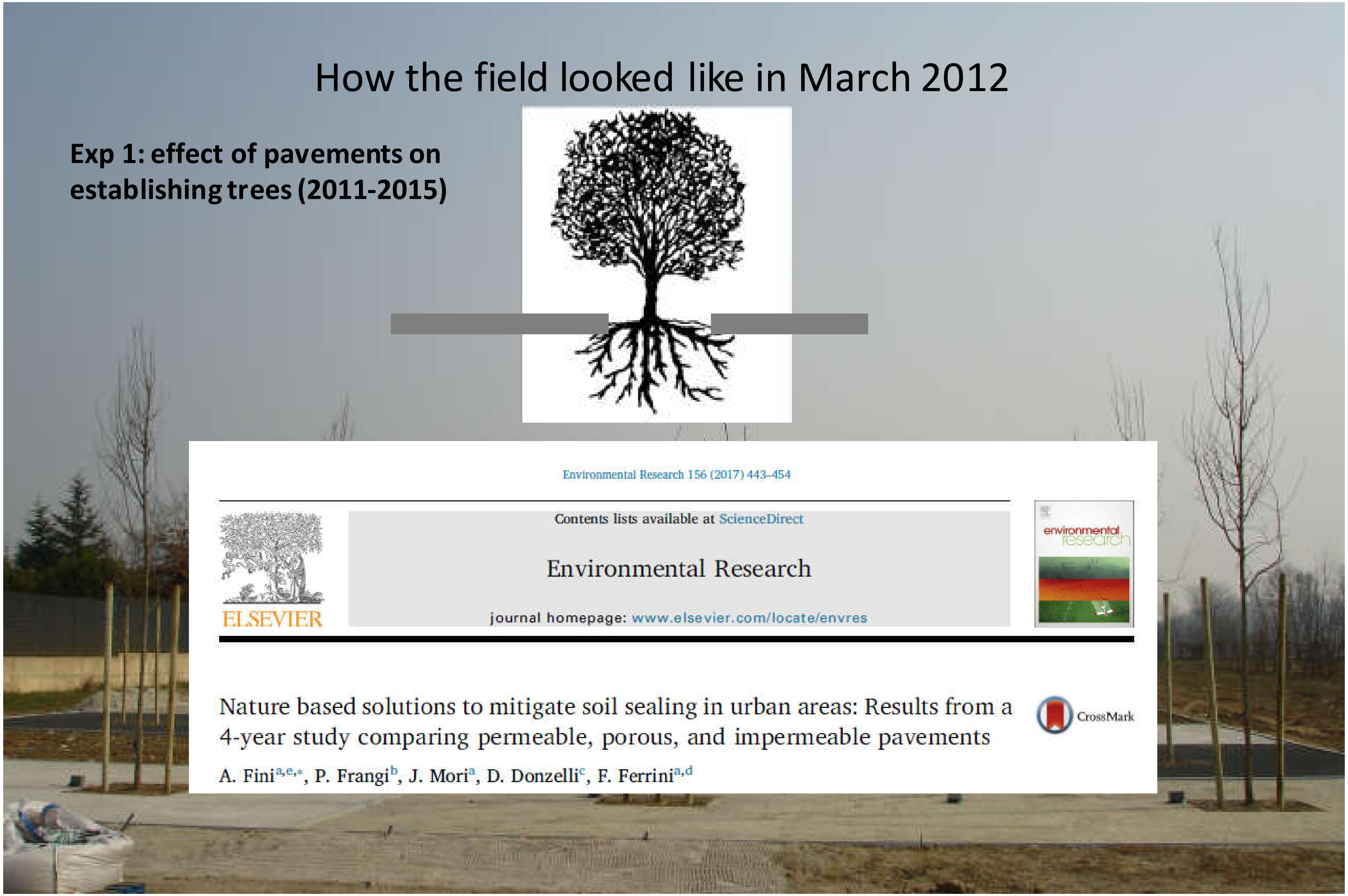


Year	Avg 2012-2020	Avg 1981-2011
Temperature (°C)	13,3	13,3
Rainfall (mm)	1251	1106

After establishment




Construction
Planting
Beginning of monitoring
Establishment
Beginning of monitoring
Root assessments and excavation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Experiment 1: establishing trees
Experiment 2: established trees



How the field looked like in March 2012

Exp 1: effect of pavements on establishing trees (2011-2015)

Environmental Research 156 (2017) 443–454

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

ELSEVIER

Nature based solutions to mitigate soil sealing in urban areas: Results from a 4-year study comparing permeable, porous, and impermeable pavements

A. Fini[a,e,*], P. Frangi[b], J. Mori[a], D. Donzelli[c], F. Ferrini[a,d]

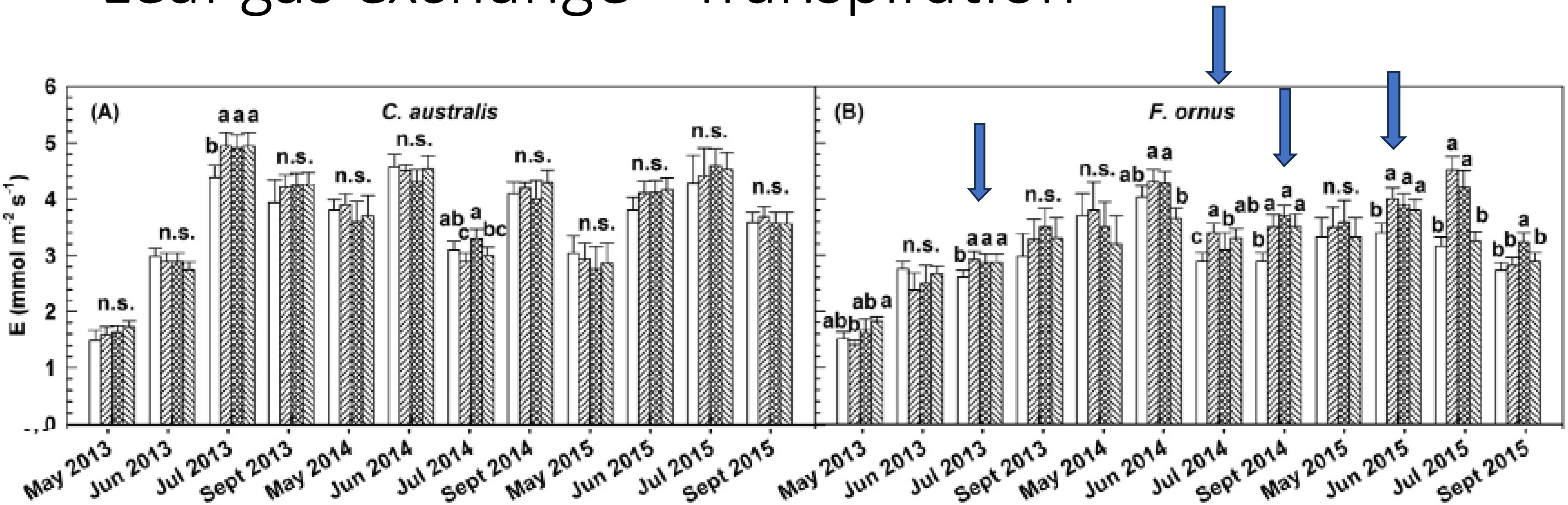
2012-2015: measurements

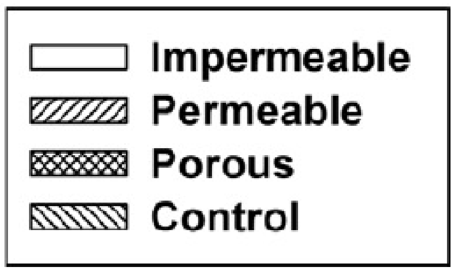
Transpiration per unit leaf area was measured in May, June, July, September from 2013 to 2015.

Transpiration indicates the amount of water transpired by 1 m^2 of full sun exposed leaf area in 1 second

It was measured using an infra-red gas analyzer at 410 ppm CO_2 and saturating (1300 μmoles m^{-2} s^{-1}) irradiance.

Leaf gas exchange - Transpiration





E indicates the amount of water transpired by 1m2 leaf area in 1 second

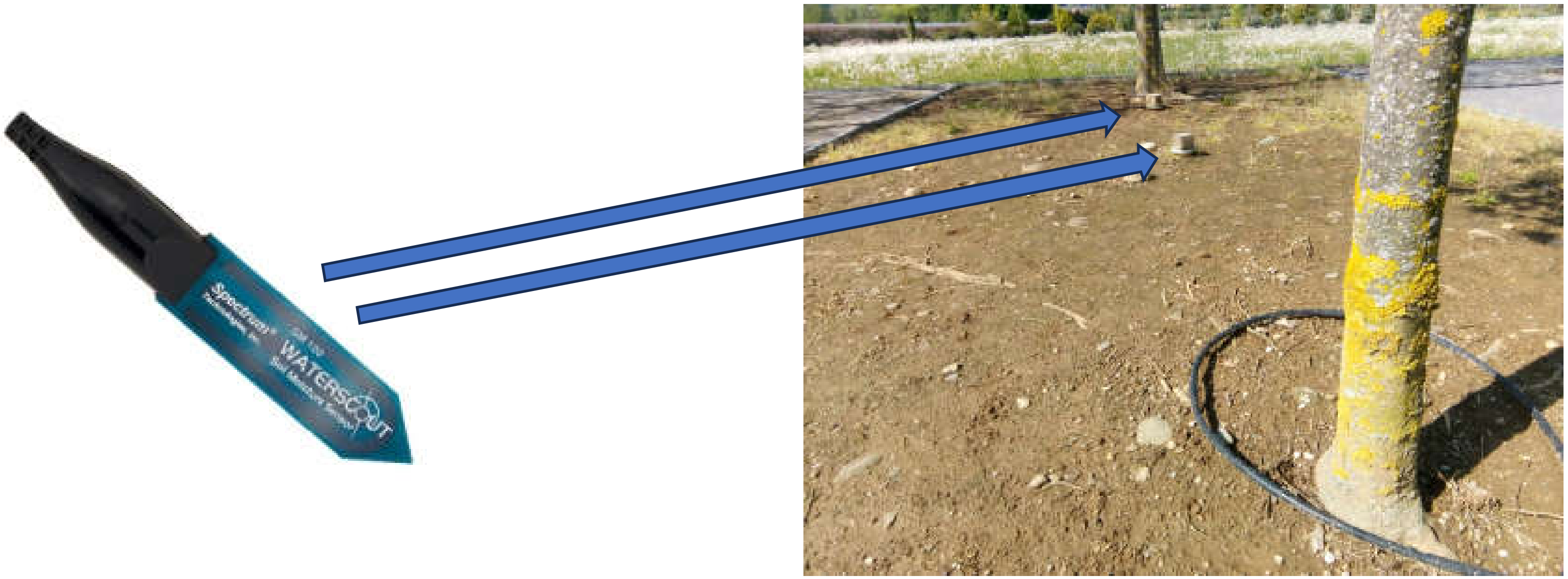
In *Celtis*, transpiration was not affected by pavement type during establishment

Fraxinus trees grown under impermeable pavements had lower transpiration compared to control in 4 of the 12 measurement dates. This did not occur for other pavement types

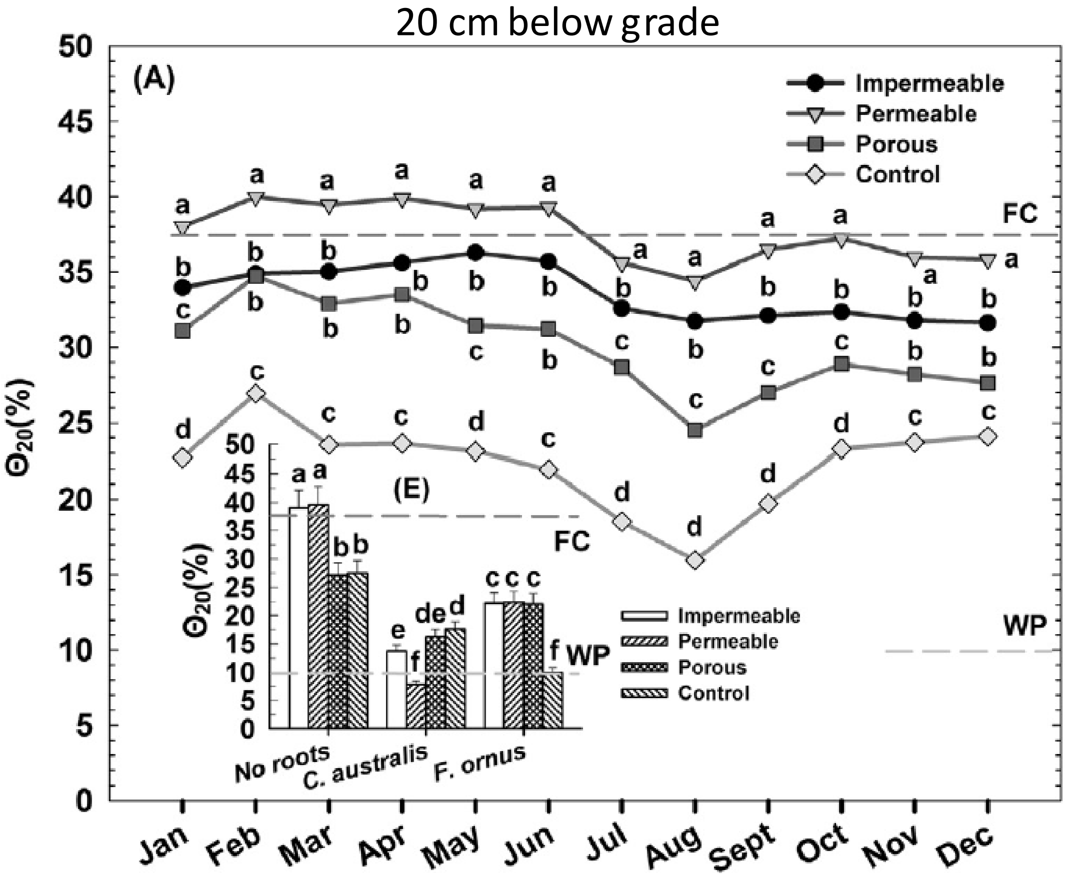
Was this due to lower soil moisture beneath asphalt?

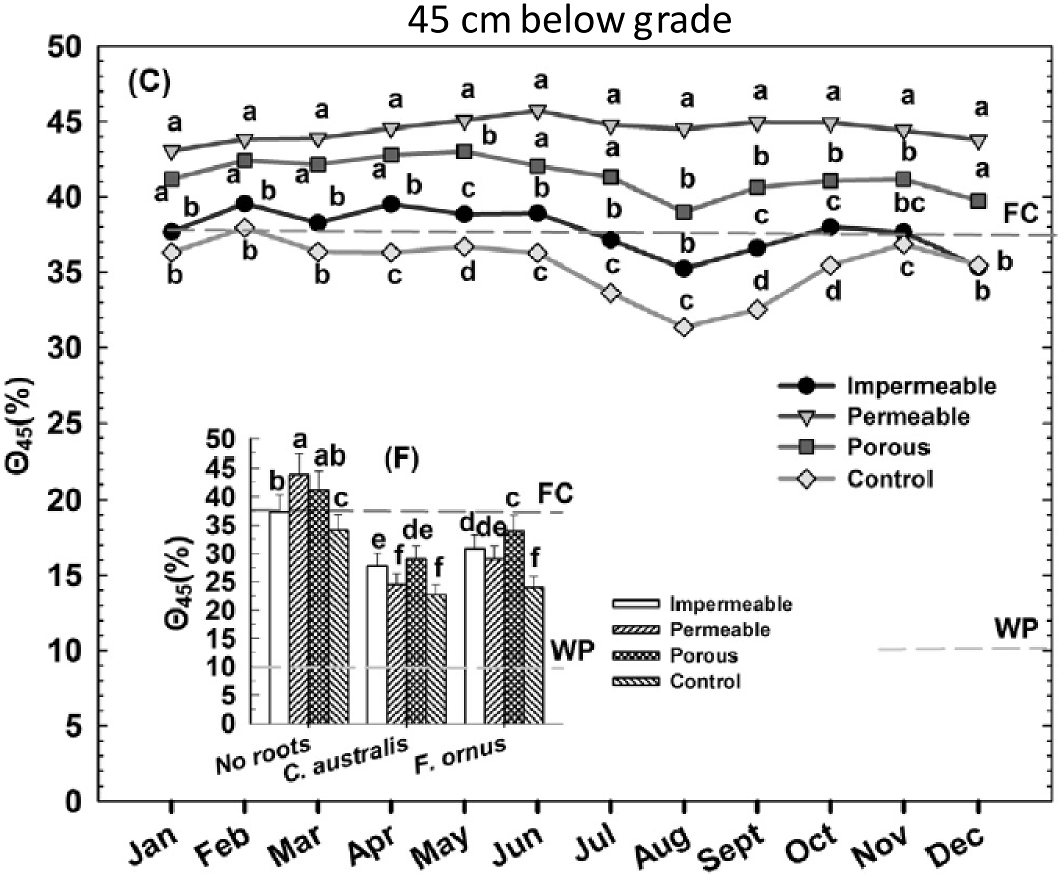
Volumetric soil moisture was measured at 20 and 45 cm below pavement surface using 96 FDR probes.

A gravimetric method was previously used to assess volumetric water content at field capacity and wilting point, which were around 37% (v/v) and 9% (v/v), respectively



Soil moisture as affected by pavements (2012-2015)





2012-2015 measurements

Plant water relations: **Pre-dawn, xylem, and midday water potential** were assessed on all plants, on the same day as leaf gas exchange. They measure the hydration of plant tissues

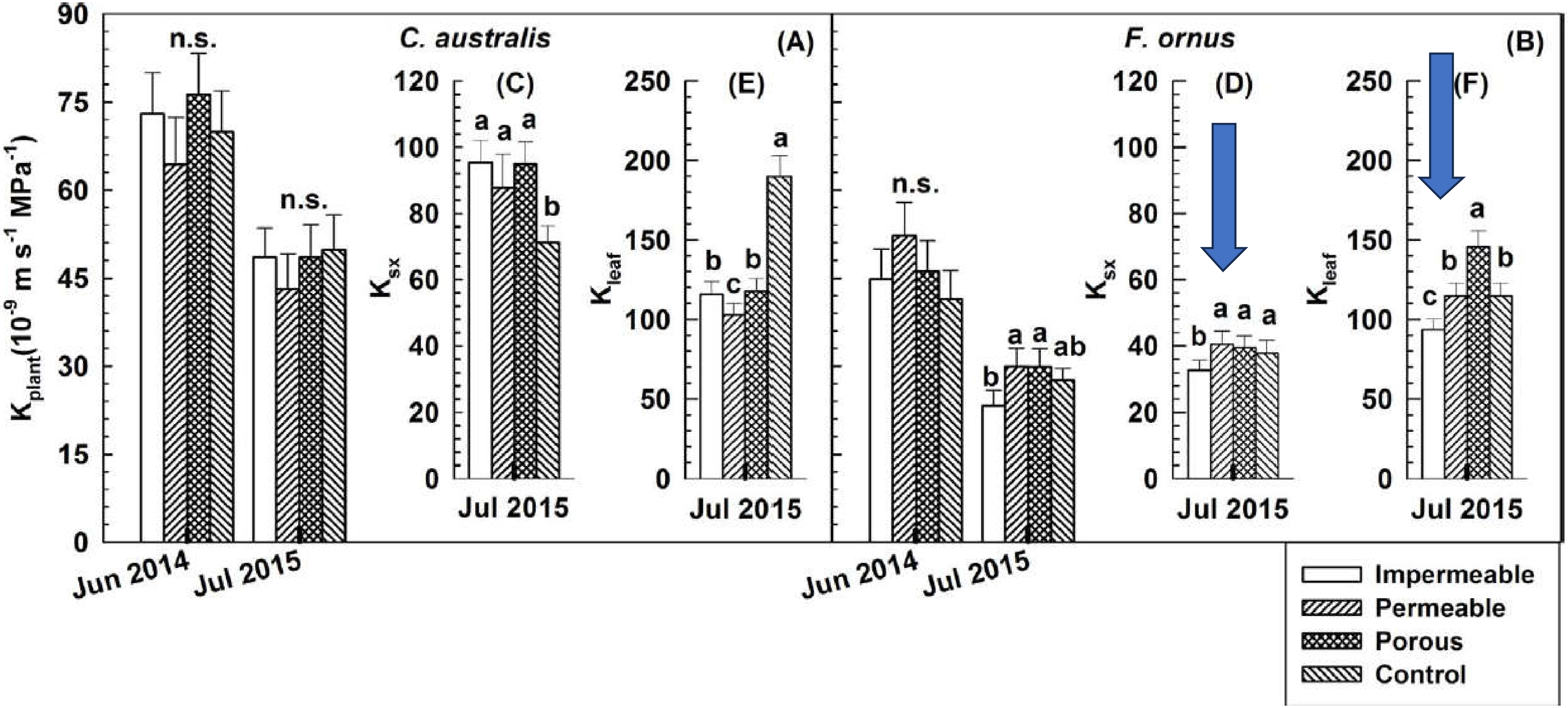
Plant conductivities: **Plant conductivity** (Ksp), **root to xylem conductivity** (Ksx) **and leaf conductivity** (Kl) were calculated from water potential and transpiration data

$$K_{sp} = \frac{E}{\Psi_{pd} - \Psi_{md}}$$

$$K_{l} = \frac{E}{\Psi_{x} - \Psi_{md}}$$

$$K_{sx} = \frac{E}{\Psi_{pd} - \Psi_{x}}$$

Is it a matter of hydraulic conductivity?



2012-2015: measurements

TREE PHYSIOLOGY – other traits

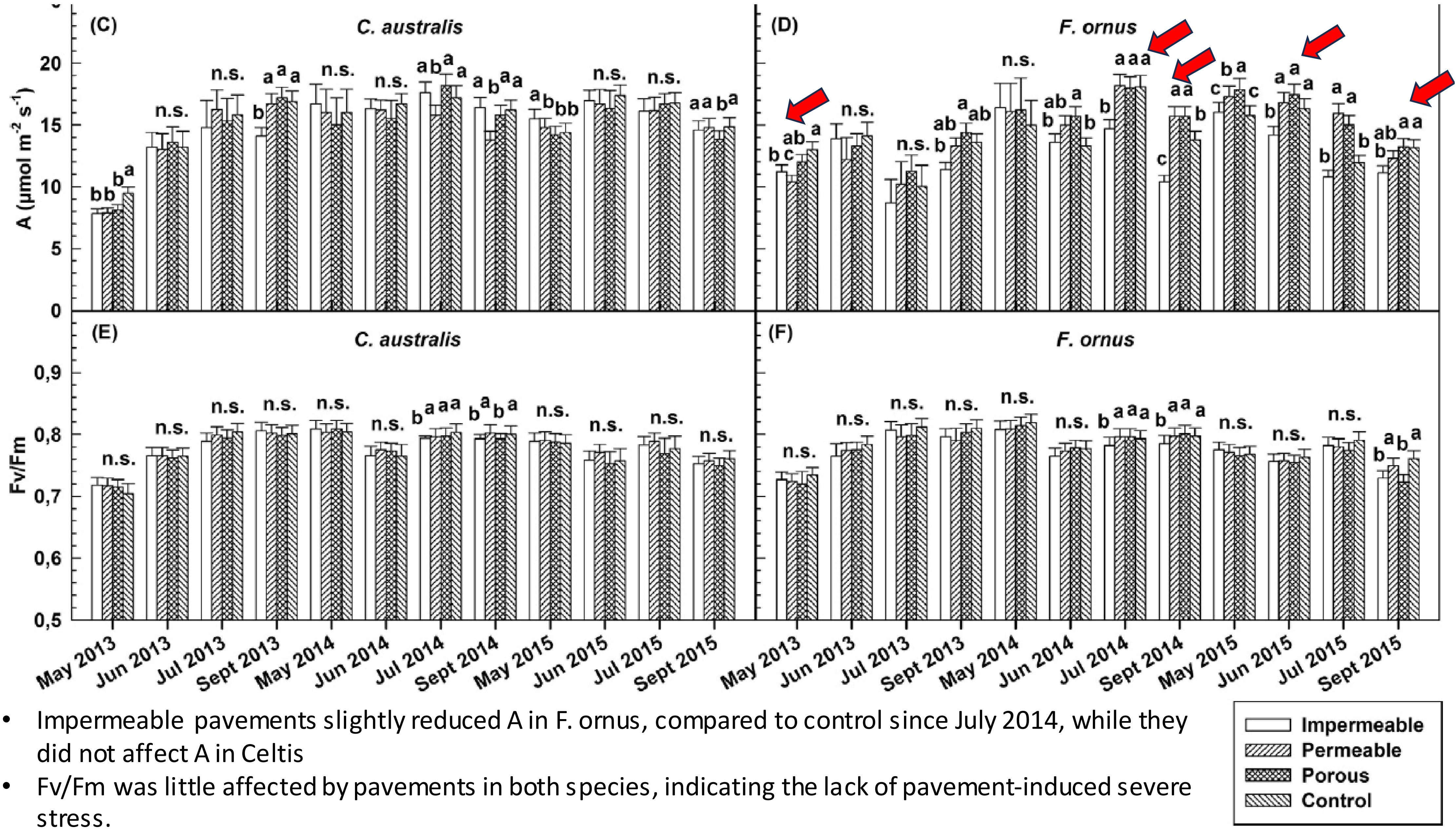
Leaf gas exchange: **CO_2 assimilation** per unit leaf area **(A)** was measured in May, June, July, September from 2013 to 2015

It is the amount of CO_2 that 1 m^2 of full sun exposed leaf removes from the atmosphere and turns into carbohydrates to sustain plant vital processes.

It was measured using an infra-red gas analyzer at 410 ppm CO_2 and saturating (1300 μmoles m^{-2} s^{-1}) irradiance.

Chlorophyll fluorescence: **the maximum quantum yield of PSII photochemistry (Fv/Fm)** was measured on dark adapted (40 minutes) leaves of all plants using a portable fluorometer.

It provides a measurement of photoinhibition experienced by the leaf. Values higher than 0,8 indicate no stress.



- Impermeable pavements slightly reduced A in F. ornus, compared to control since July 2014, while they did not affect A in Celtis
- Fv/Fm was little affected by pavements in both species, indicating the lack of pavement-induced severe stress.

Effects of pavements on stem diameter and shoot growth

Table 3
Effects of different pavement types on stem relative growth rate (RGRstem, micron cm^{-1} day^{-1}) and shoot growth (cm). Different letters within the same year of measurement and species indicate significant differences among pavement treatments using Duncan's MRT.

	RGR_{stem} (micron cm^{-1} day^{-1})			Shoot growth (cm)			
Treatment	2012–13	2013–14	2014–15	2012	2013	2014	2015
Celtis australis							
Impermeable	9.84 a	18.03 a	13.87 a	33.40 a	30.00 a	38.57 c	44.10 b
Permeable	8.14 a	19.13 a	12.35 a	33.07 a	21.60 b	47.92 ab	43.50 b
Porous	11.98 a	18.18 a	12.94 a	23.19 b	31.40 a	50.10 a	47.80 b
Control	8.97 a	17.18 a	15.20 a	22.90 b	19.30 b	41.88 bc	58.50 a
Fraxinus ornus							
Impermeable	9.53 a	7.46 b	5.96 ab	17.11 c	8.40 c	24.52 a	25.30 a
Permeable	6.24 b	6.66 b	6.97 a	24.88 b	22.20 a	26.14 a	18.60 b
Porous	5.24 b	9.01 a	6.66 a	49.54 a	16.20 b	25.28 a	24.20 a
Control	5.83 b	10.03 a	5.04 b	24.70 b	16.80 b	30.95 a	18.90 b

- No evidence that pavements affected stem DBH growth or shoot elongation was found.
- *Celtis* displayed much faster growth rate than *Fraxinus*

TAKE HOME MESSAGE: we found little evidence that impermeable pavements impair establishment due to lower soil moisture availability, compared to trees growing in bare soil.
Permeable and porous pavements can increase moisture availability, compared to control. This may be an advantage for species hard to transplant, such as ash.

Experiment 2: established trees (2016-2020)

TREE FUND
Cultivating Innovation

Landscape and Urban Planning 226 (2022) 104501

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

ELSEVIER

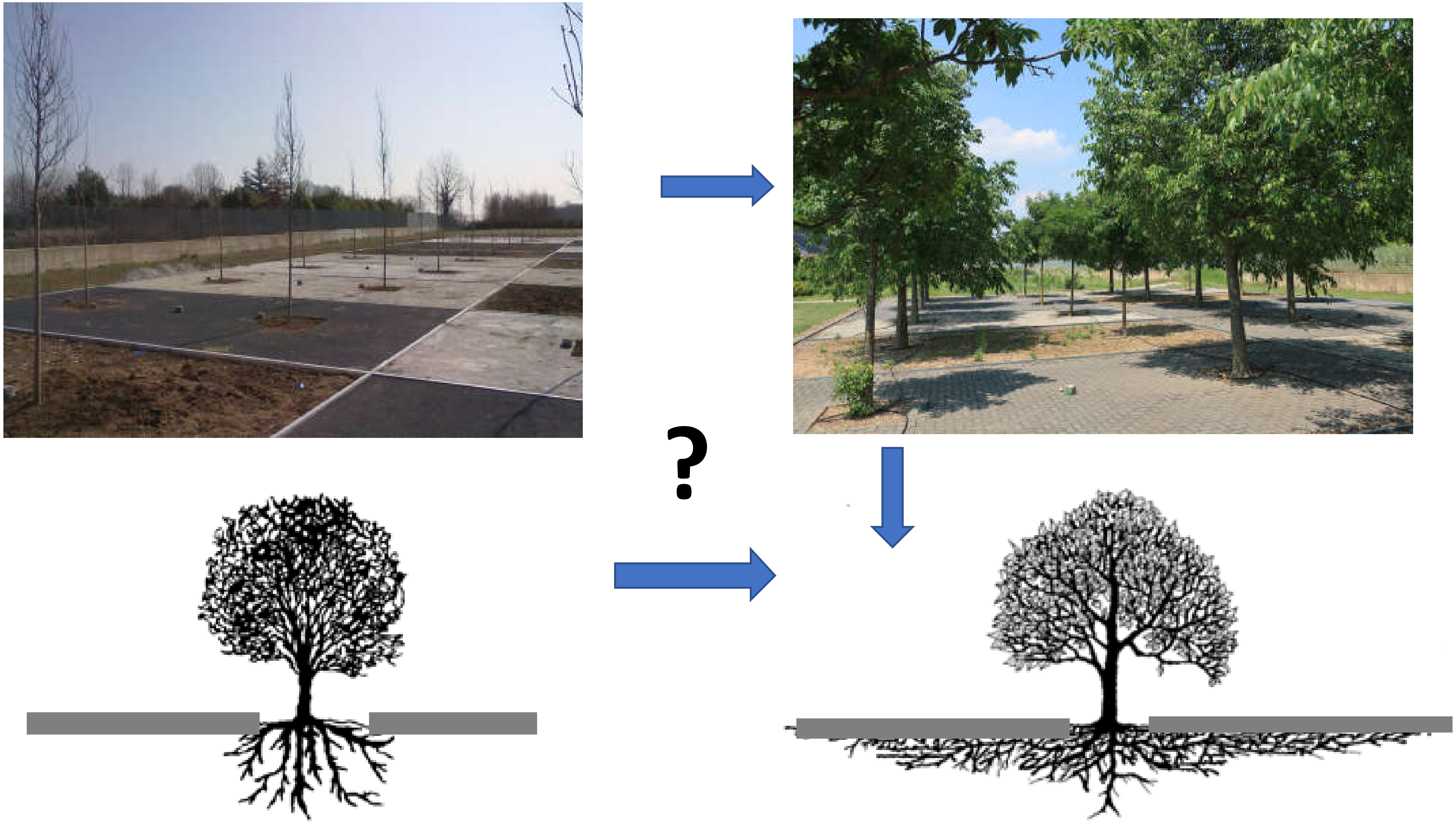
Research Paper

Effects of pavements on established urban trees: Growth, physiology, ecosystem services and disservices

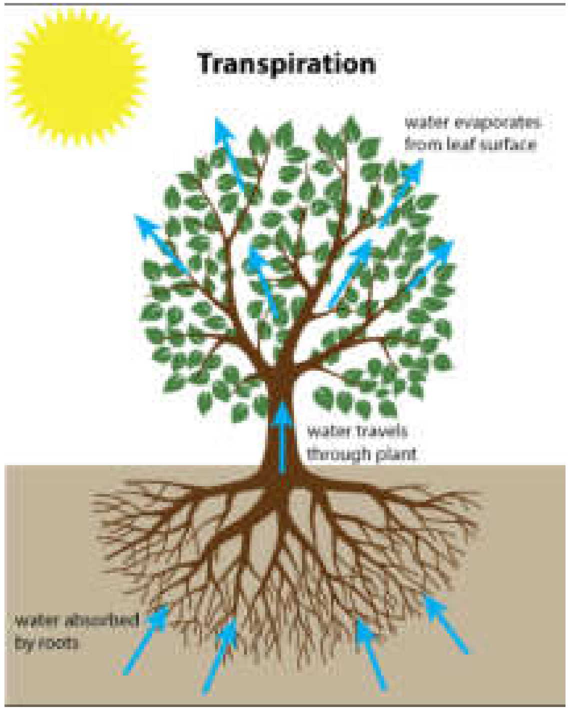
Alessio Fini [a,*], Piero Frangi [b], Sebastien Comin [a], Irene Vigevani [a,e], Andrea Alberto Rettori [c], Cecilia Brunetti [d], Bárbara Baesso Moura [e], Francesco Ferrini [e]

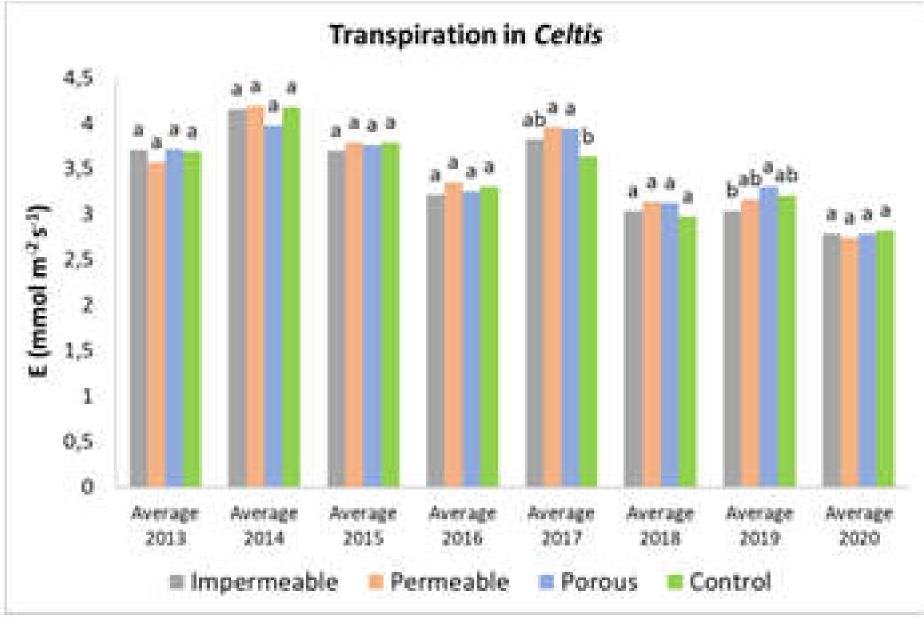
[a] Dipartimento di Scienze Agrarie e Ambientali – Produzione, Territorio, Agroenergia, Università degli Studi di Milano, Milano (MI), Italy
[b] Fondazione Minoprio, Vertemate con Minoprio (CO), Italy
[c] Studio Associato Planta, Rosta (TO), Italy
[d] Istituto per la Protezione Sostenibile delle Piante – Consiglio Nazionale delle Ricerche, Sesto Fiorentino (FI), Italy
[e] Dipartimento di Scienze e Tecnologie Agrarie, Alimentari, Ambientali e Forestali, Università degli Studi di Firenze, Firenze (FI), Italy

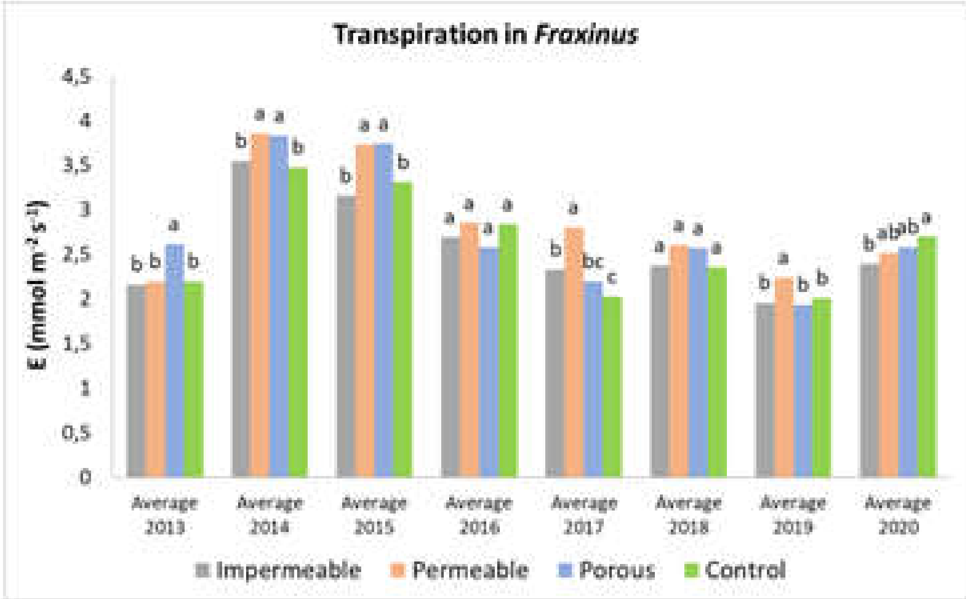
Establishment occurred in 2015, as determined by several roots observed in the measurement holes outside the planting pit



Traspiration per unit leaf area did not change much over time

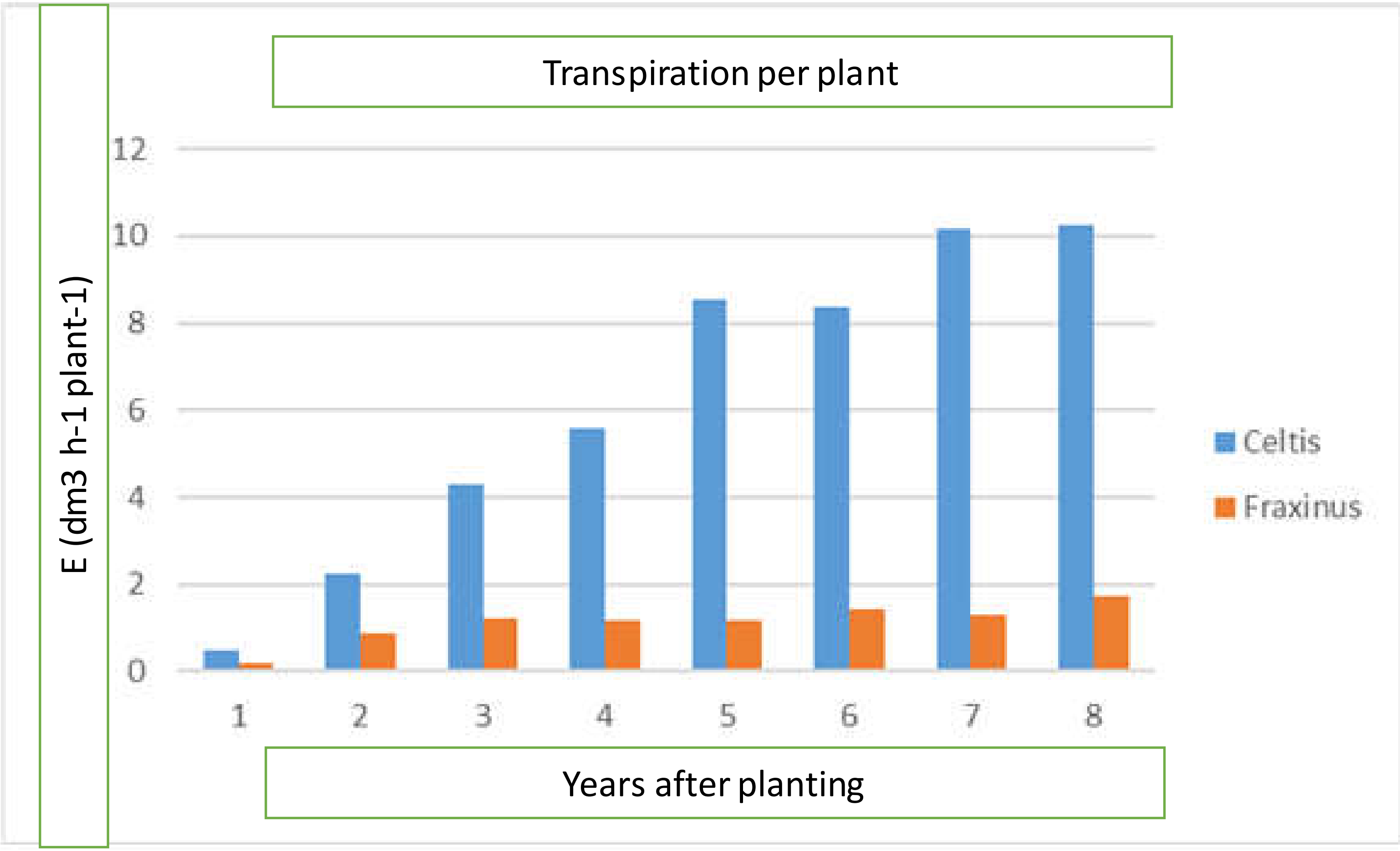




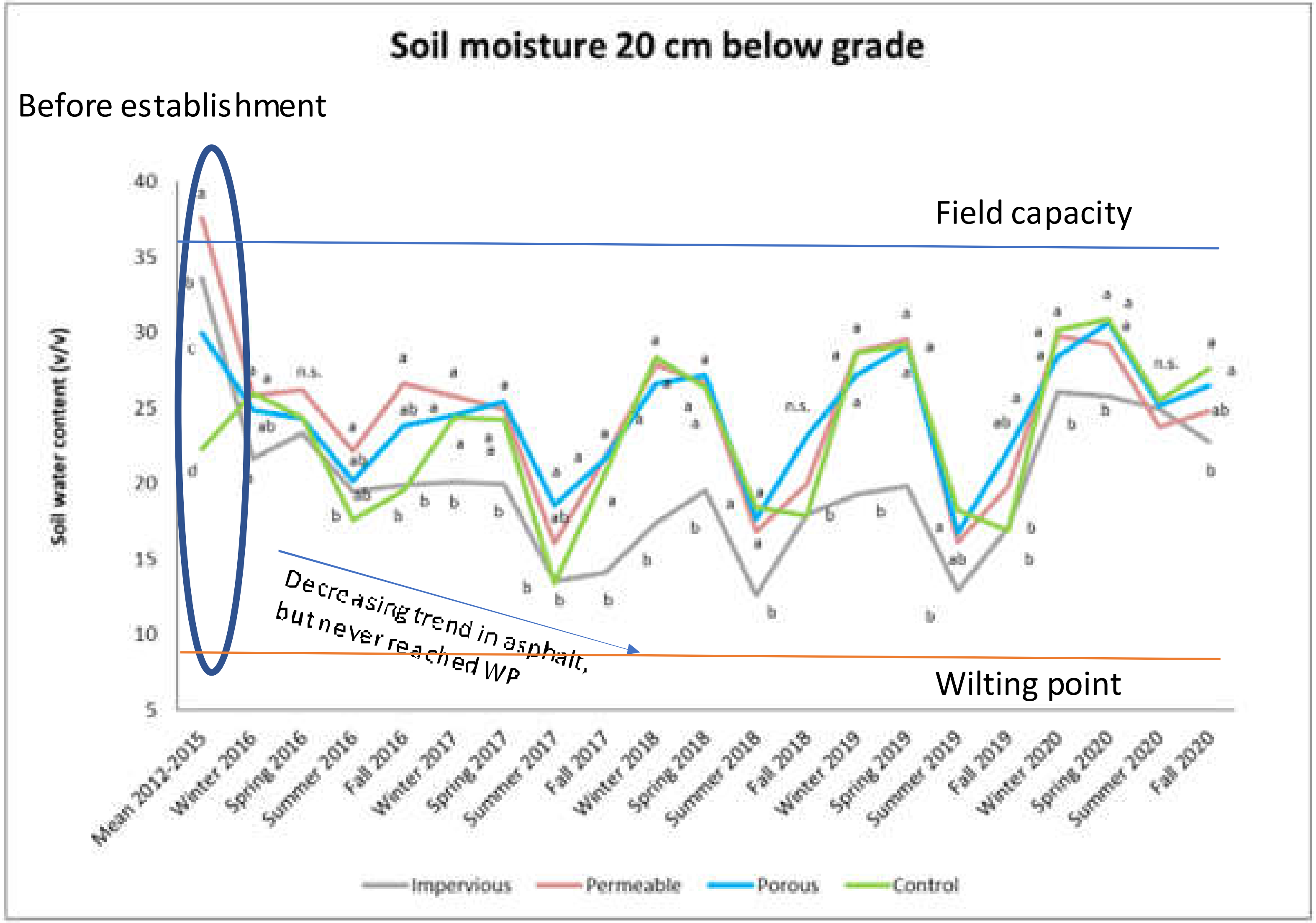


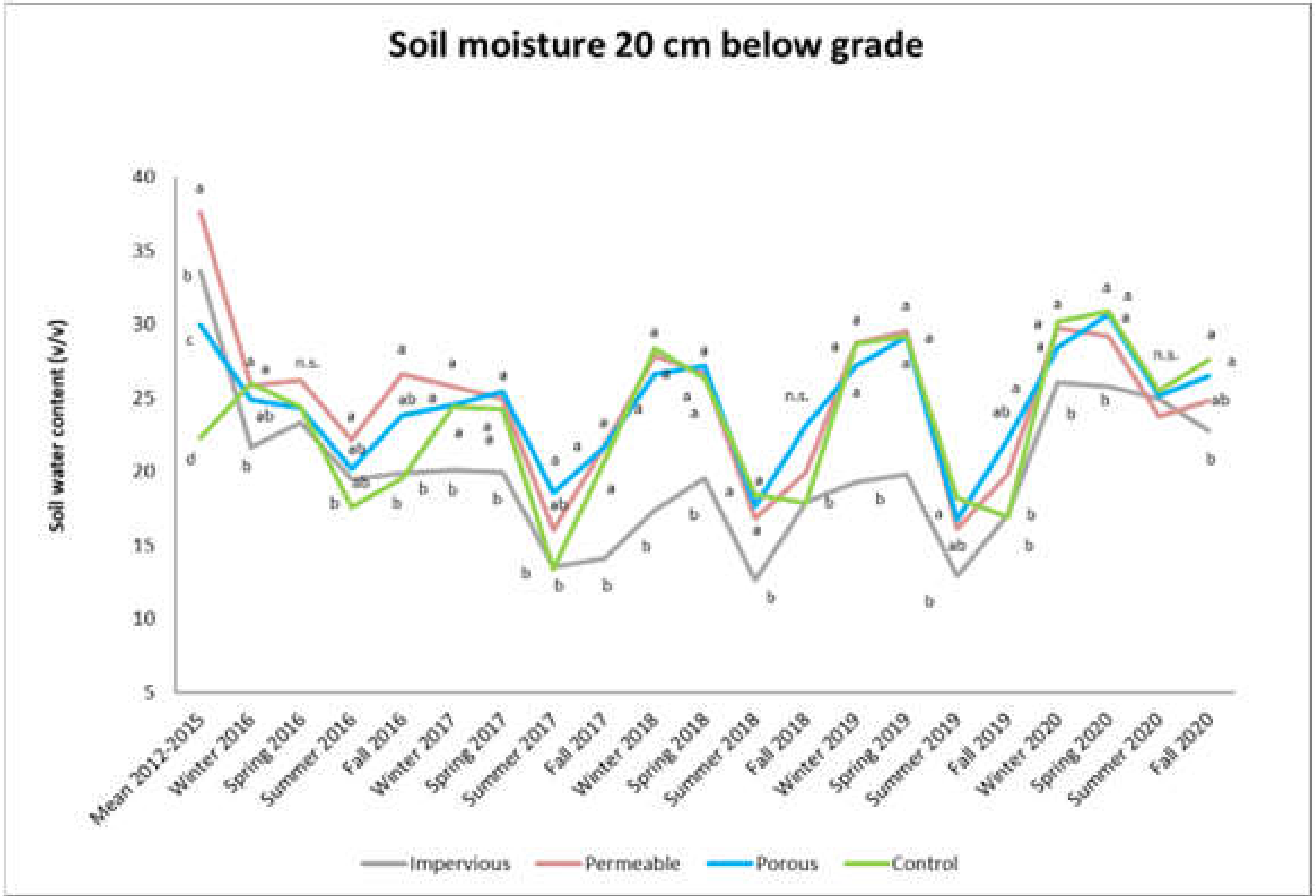
But transpiration per plant did

Transpiration was upscaled from unit leaf area to the whole tree using a big leaf model: Etree = E * CPA * (1-e(-k/LAI))/k * 3600 (s h- 1)
Where CPA is crown projection area; LAI is Leaf Area Index and k is is the extinction coefficient for solar radiation gradient in a canopy



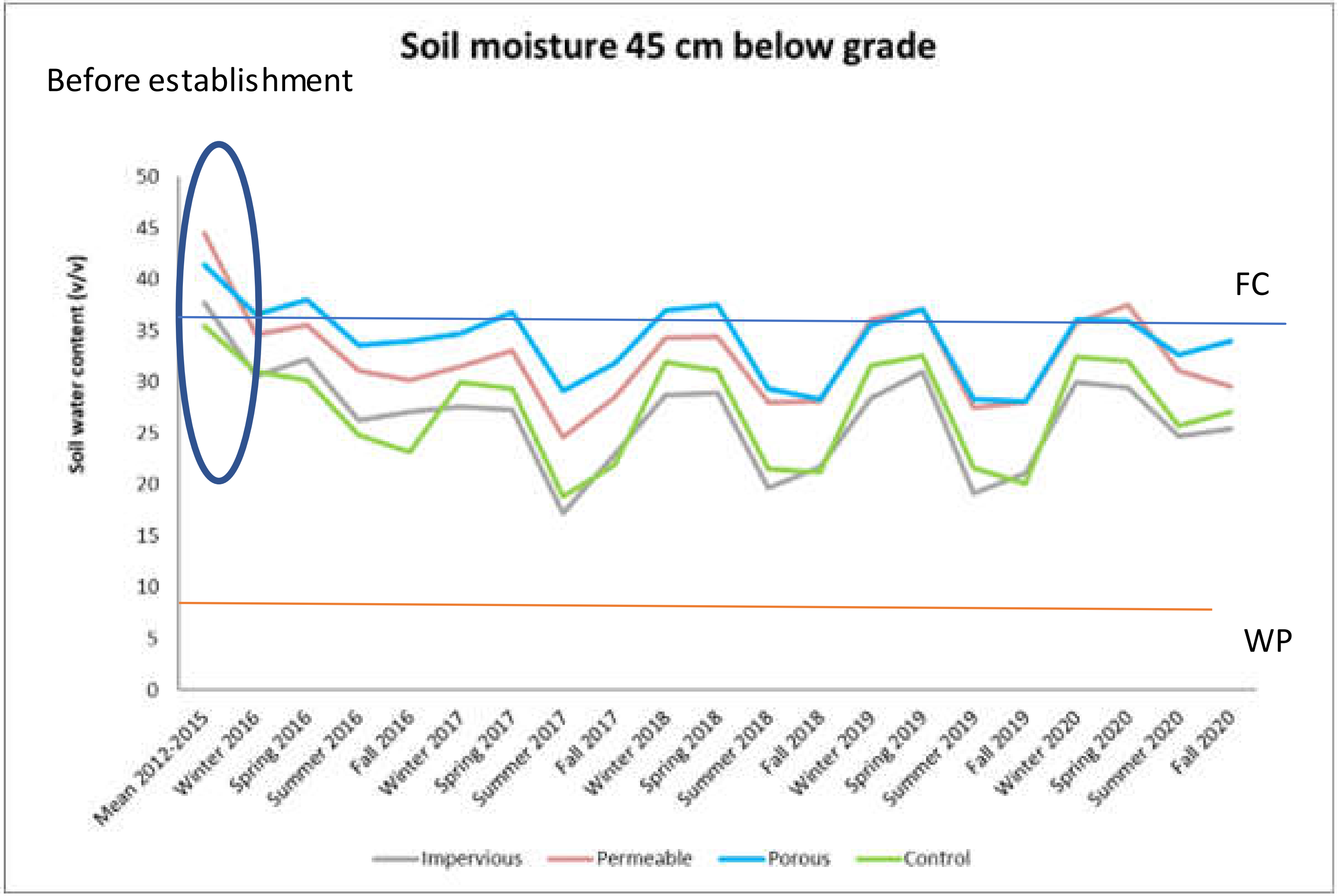
Soil moisture after establishment



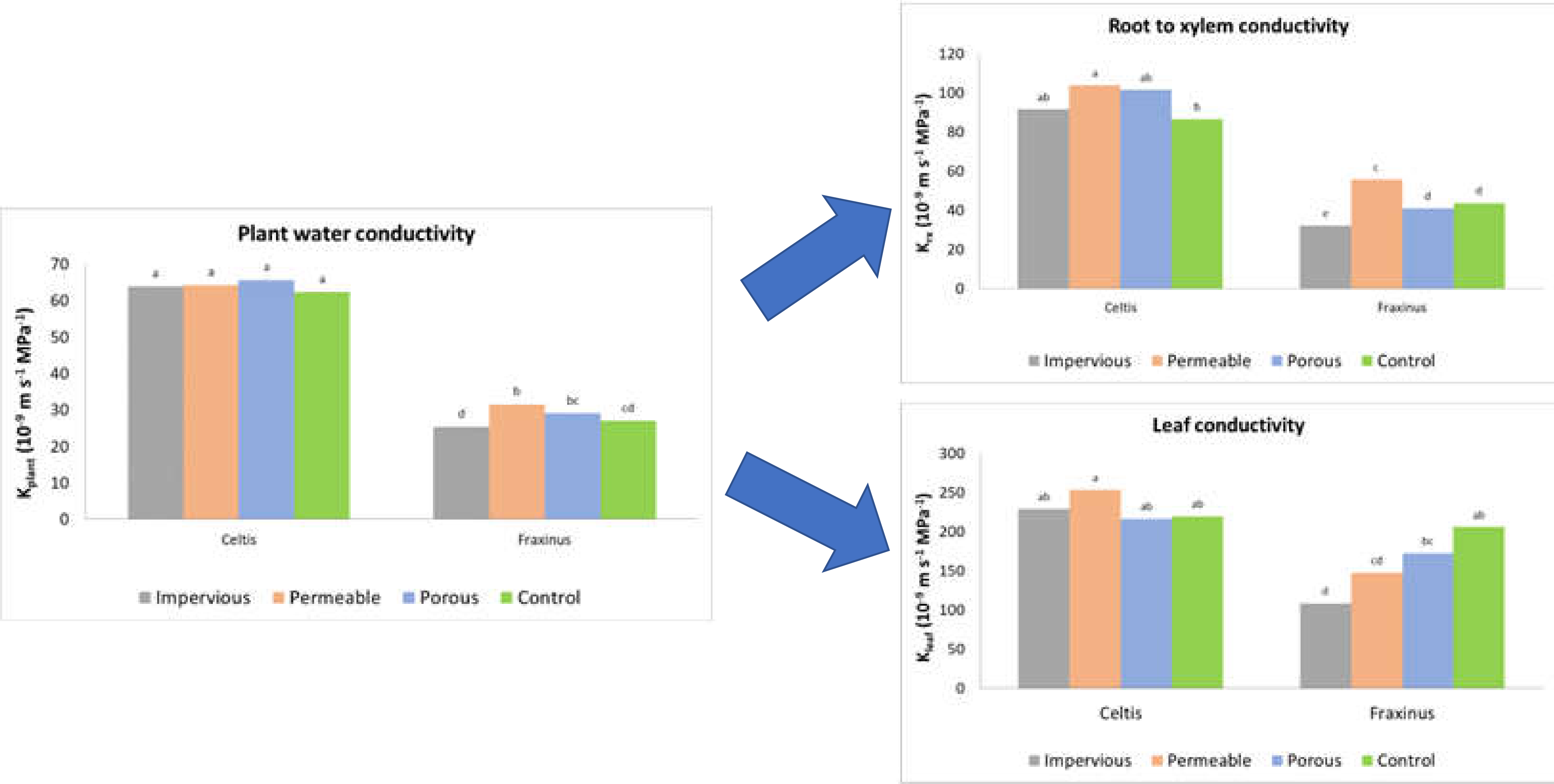


Major differences in winter and spring than in summer and fall identify a slower rehydration during the rainy period rather than a higher dehydration during summer

Soil moisture after establishment



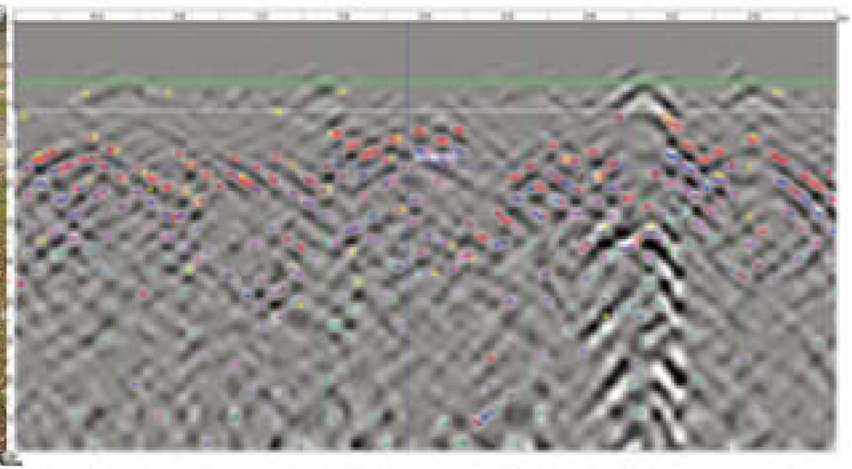
Plant hydraulic conductivities after establishment



Root detection – non invasive

1 – Ground Penetrating Radar (in cooperation with Studio Planta):

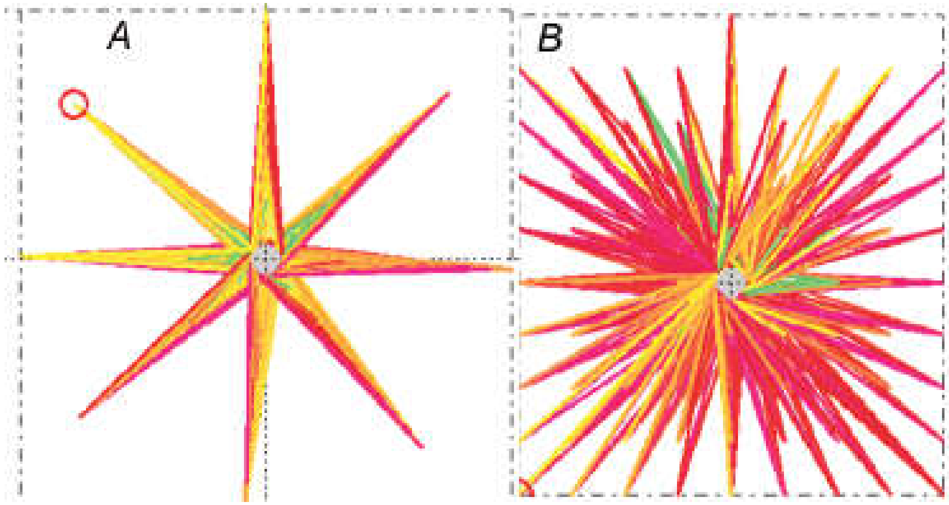
- Tree Radar GPR system (TRU™ Model, Tree Radar Inc., Silver Spring, MA, USA) equipped with a portable TerraSIRch Subsurface Interface Radar system (SIR-3000, GSSI, Salem, NH) and a 900 MHz antenna
- Twenty cm pitch concentric virtual trenches were scanned
- Three soil horizons were investigated (0-30 cm; 30-60 cm; 60-90 cm)
- TreeWin TBA (V3.8.1) was used to generate the root morphology maps (Bassuk et al., 2011)



Root detection – non invasive

2 – Sonic Tomography (In cooperation with Dendrotec):

- ArboradixTM was used on 16 trees
- Measurements were done before and after removing the pavements
- Measurements were conducted using two arrangements: the star arrangement (A) did not provide enough spatial information and was replaced by a radial arrangement (B)



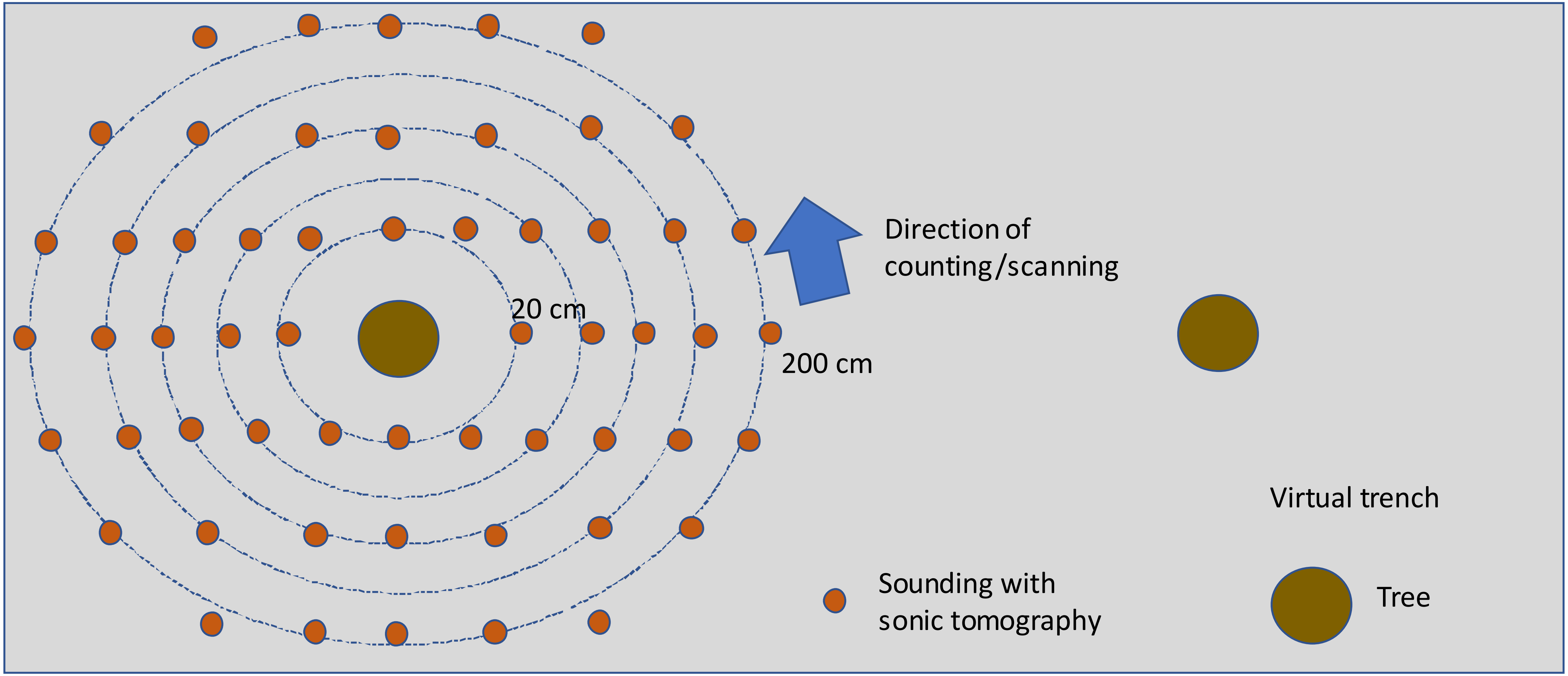
Root detection – validation

3 – Suction excavator, AirpadeTM, and manual count

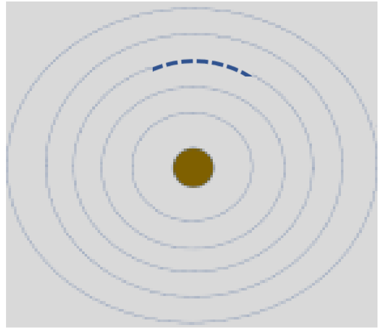
- Pavements were removed, and roots exposed using soft-dig techniques down to 30 cm below grade
- Roots with diameter larger than 1 cm were manually counted along twenty cm pitch concentric transects
- 4 individual roots per tree were cut at the flare and their length and diameter at the attachment were measured. Then, fine to coarse roots separated and weighed (FW and DW)



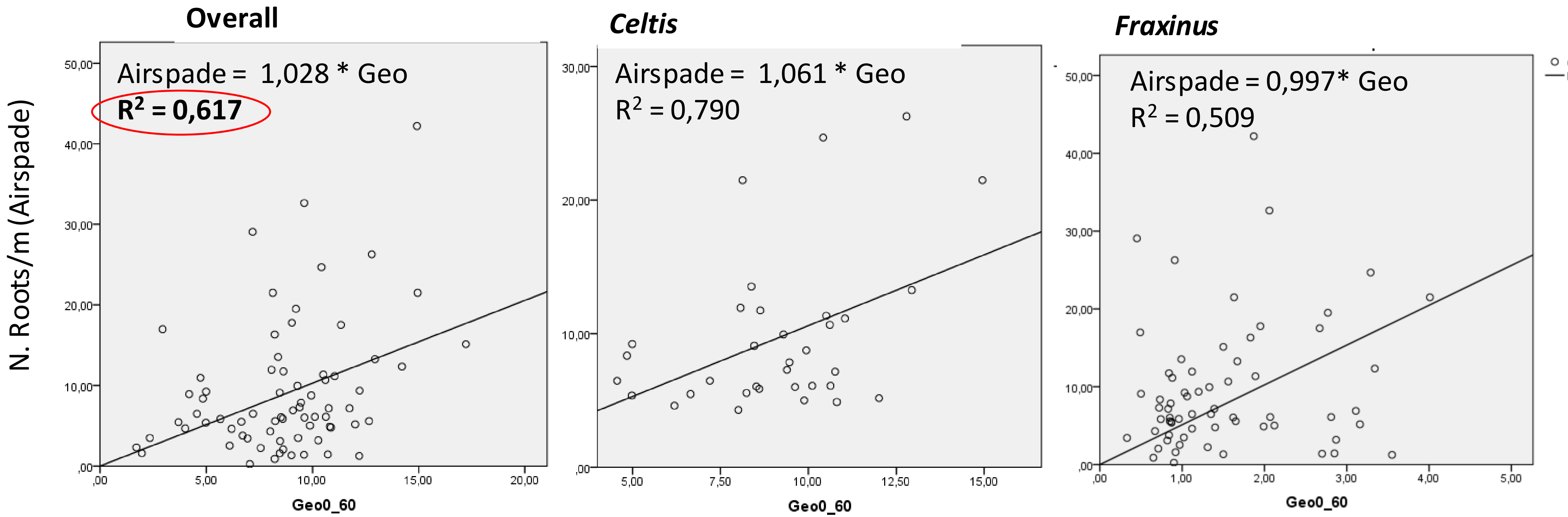
Root detection – validation



Root linear density: Manual count vs. GPR

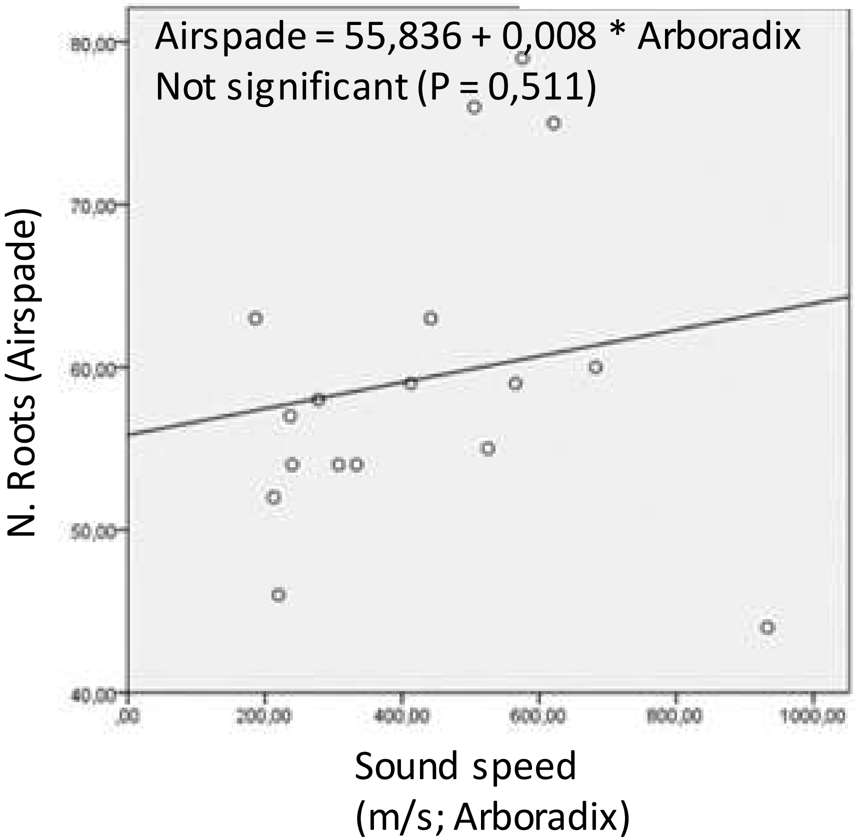


- It is calculated as total root count over the circumference of the trench
- The number of roots per m trench yields much better correlations between the two methods
- Comparison between detection methods were performed at a 0-60 cm depth

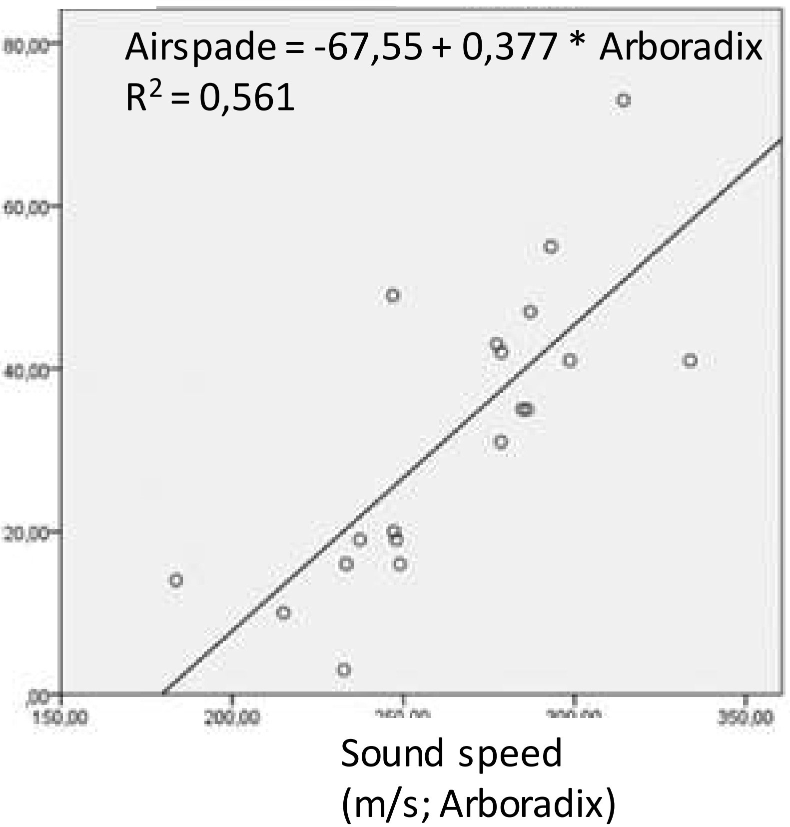


Arboradix Vs. Manual count

Celtis



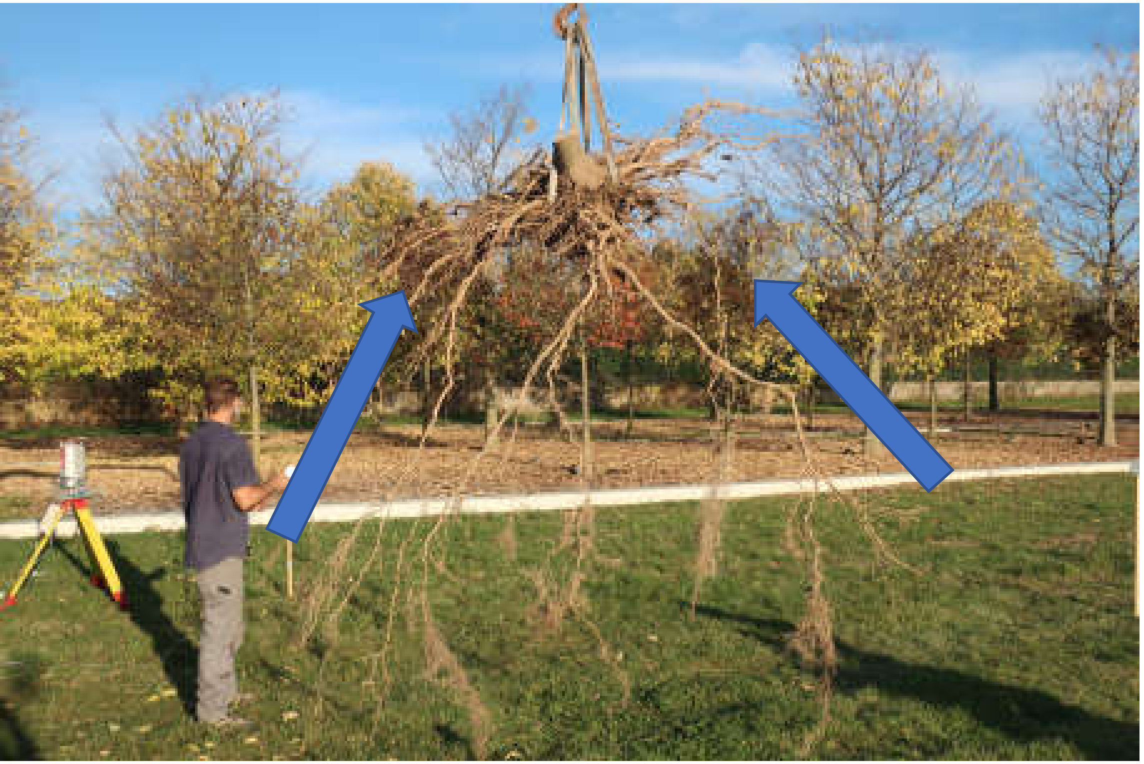
Fraxinus

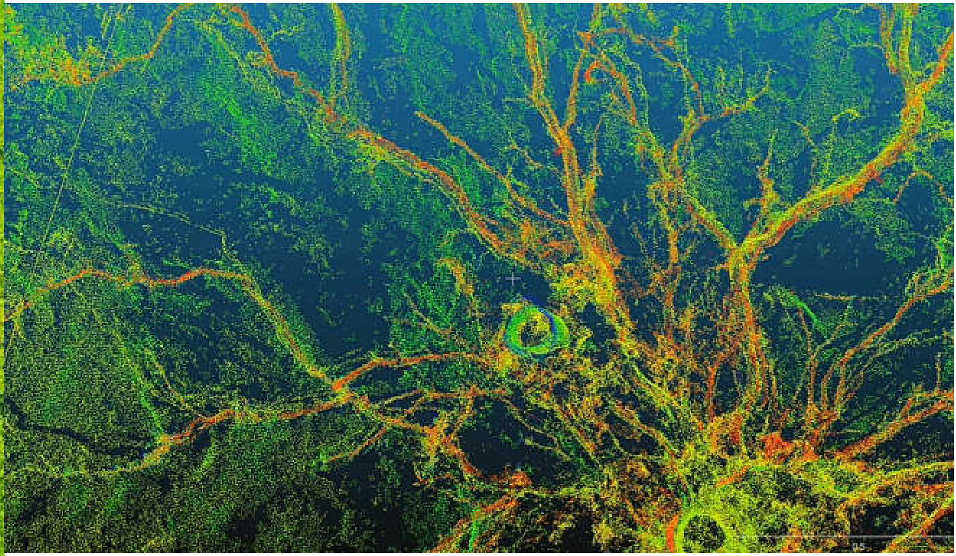


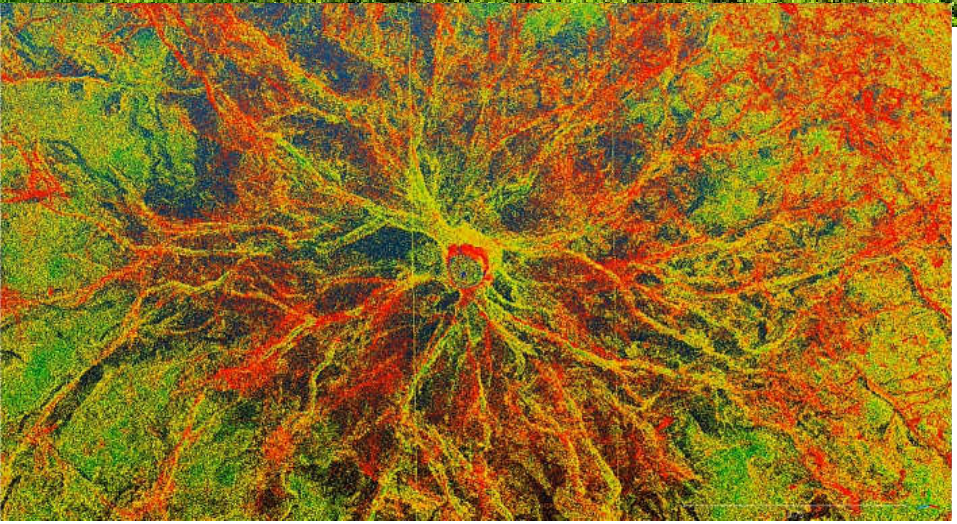
In *Fraxinus*, better correlations were found between sound speed and total root number (R2 = 0,561) than between sound speed and root n. per meter scan (R2 = 0,439)

Arboradix Vs. Manual count

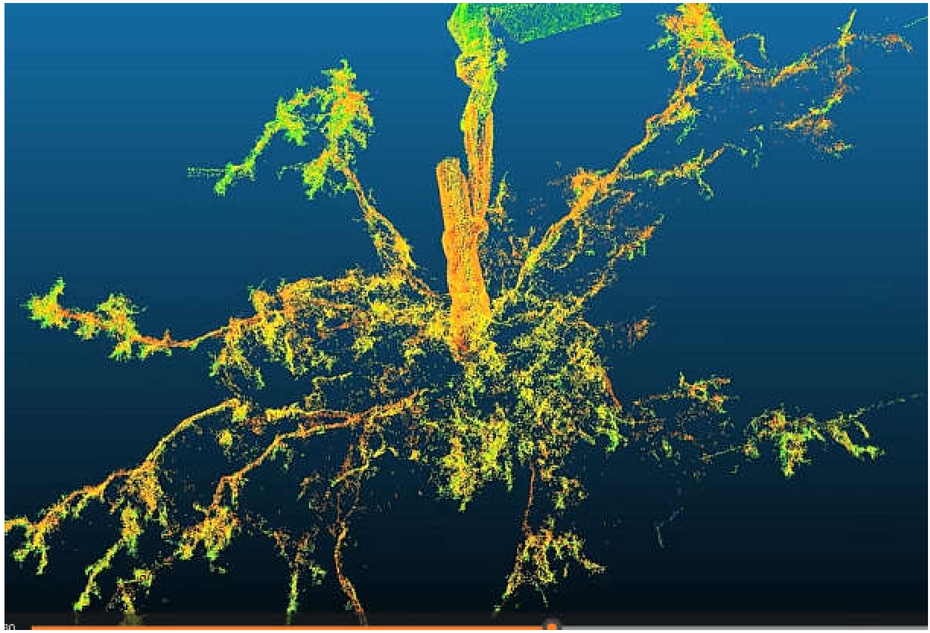
Well-spaced, straightforward roots (*Fraxinus*) yielded much better Arboradix estimates than densely packed roots with some circling (*Celtis*)



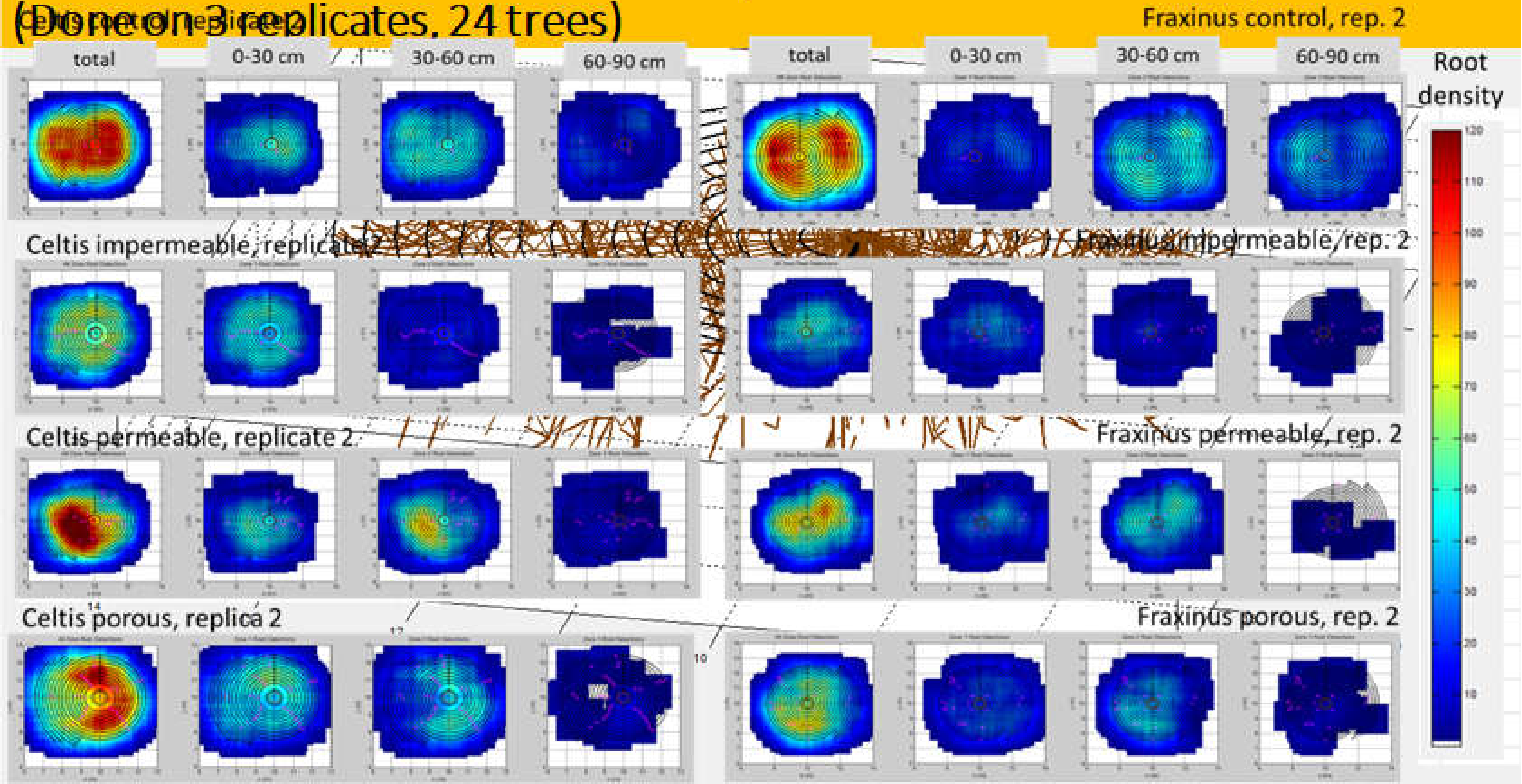


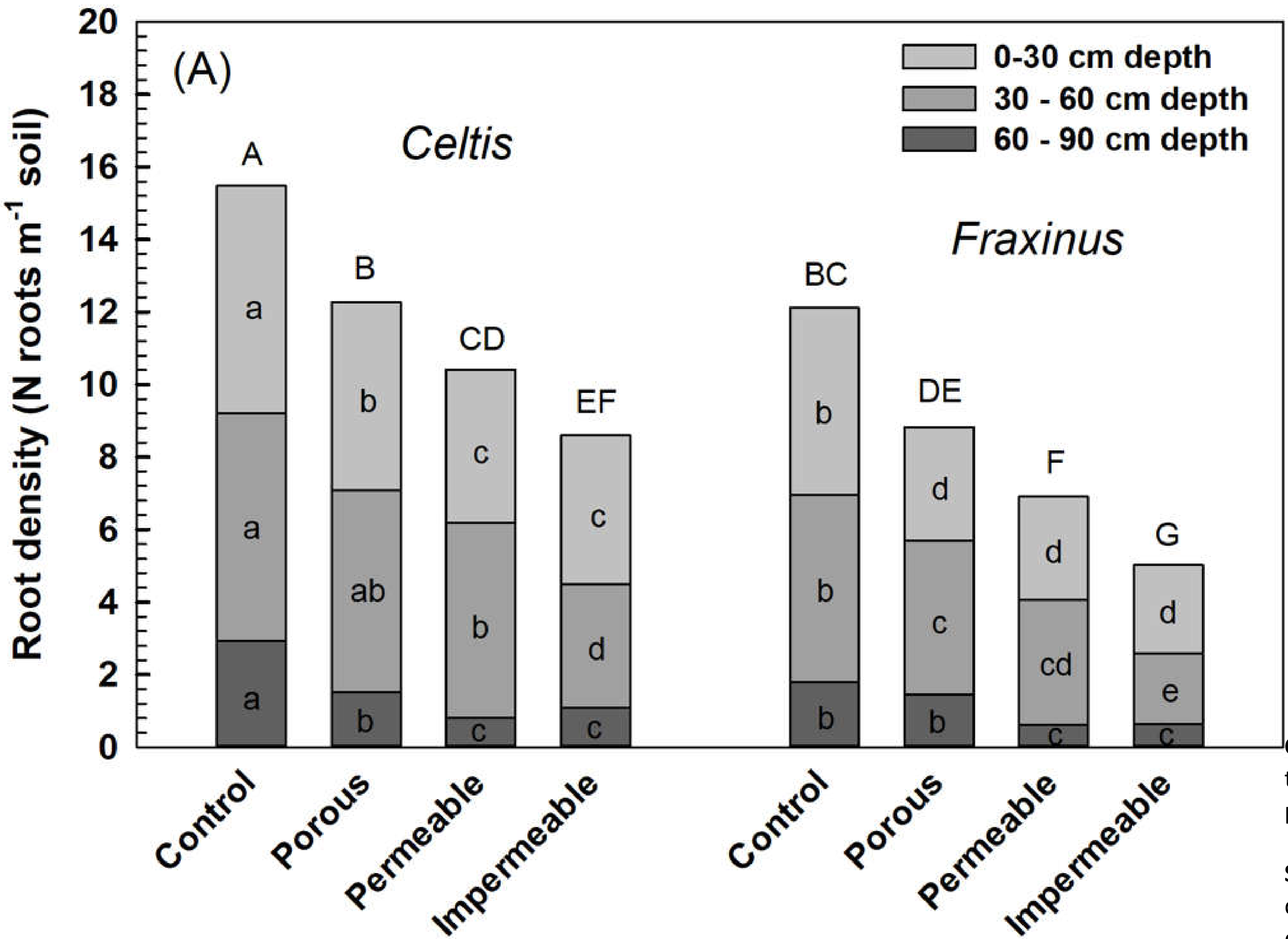


Lidar



GPR was used to assess the effects of pavements on root density (Done on 3 replicates, 24 trees)

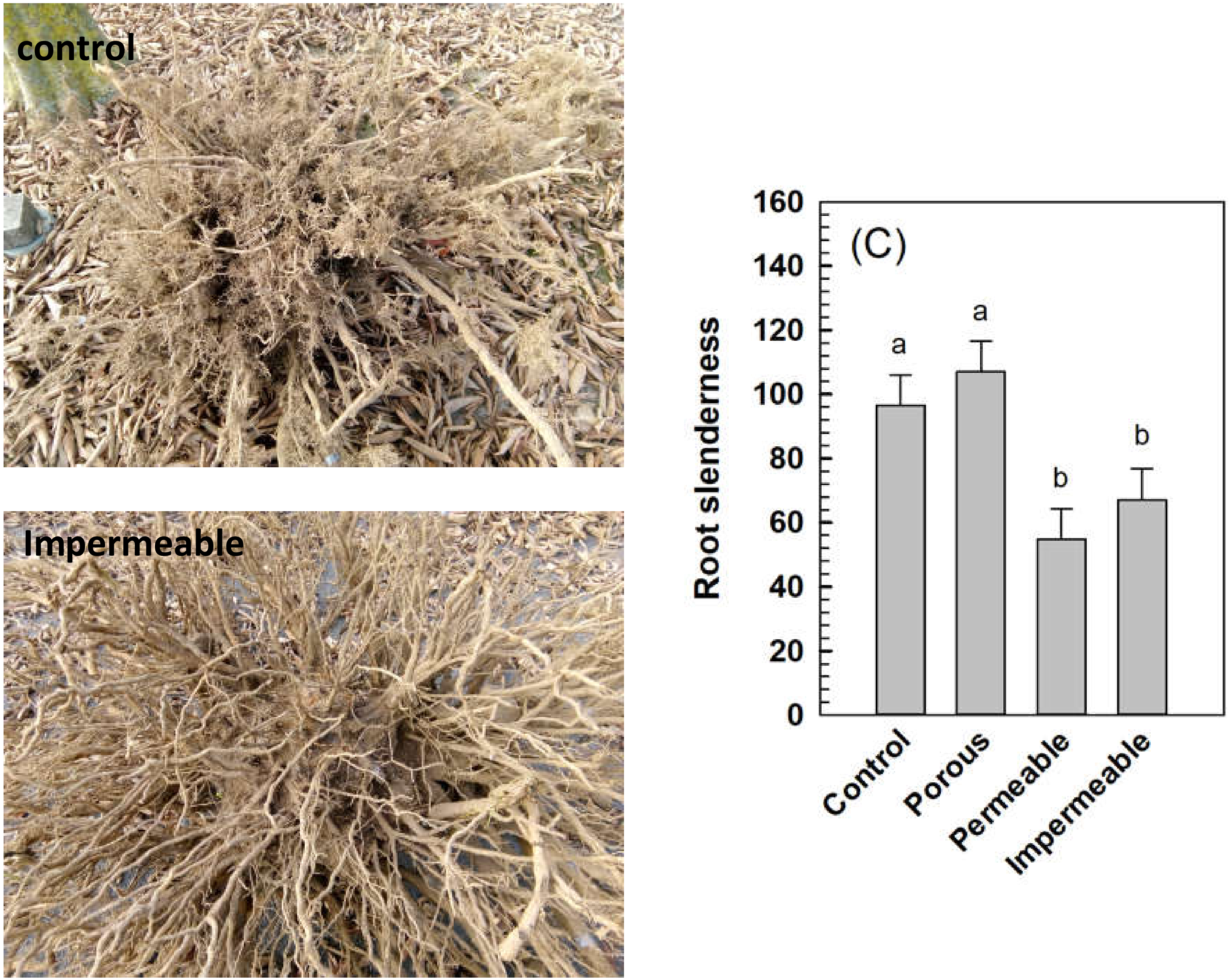




- Eighty-five to **92% of roots** were located in the **uppermost 60 cm** of soil;
- **Impermeable pavements increased** the fraction of **roots located in the uppermost 30 cm** below grade (47.7%) compared to other treatments (40.6%);
- **control trees had more deep roots** (> 60 cm below grade, 17.3%) compared to porous (14.4%), impermeable (12.7%) treatments, and permeable pavements (8.4%).

Capital letters indicate differences in total root density among species and pavement treatments at p<0,01

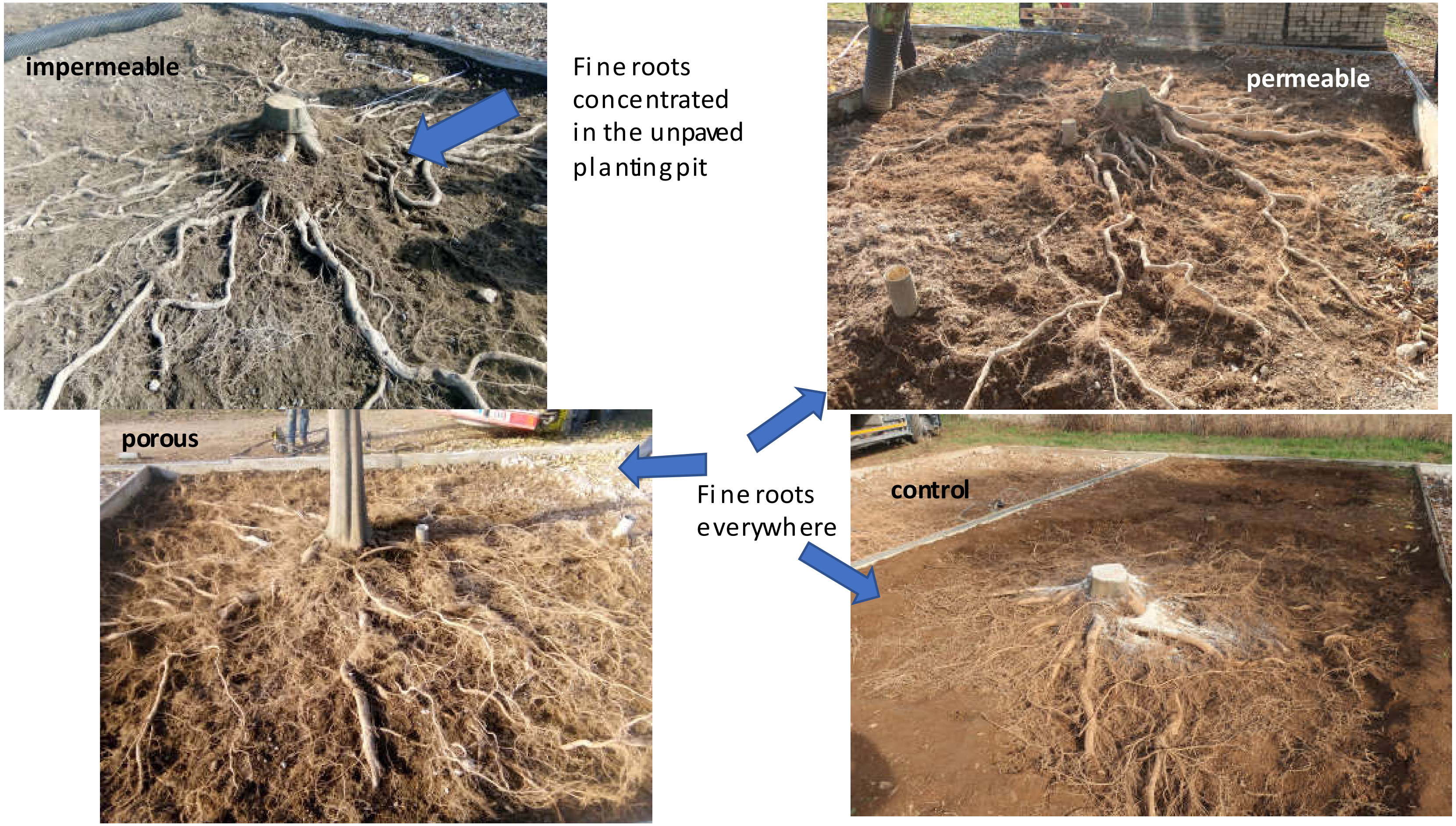
Small letters indicate significant differences in root density within a depth range among species and pavement treatments at p<0,01



control
Impermeable
(C)
Root slenderness
0
20
40
60
80
100
120
140
160
a
a
b
b
Control
Porous
Permeable
Impermeable

Root biomass- fine vs. coarse roots

Pavement	DWfine/DWwoody
Impermeable	0,03 c
Permeable	0,05 bc
Porous	0,12 a
Control	0,08 b


impermeable
Fine roots concentrated in the unpaved planting pit
permeable
porous
Fine roots everywhere
control

Root-associated microbiota (in cooperation with University of Pisa)

- In October 2020, 3 root+soil sub-samples (approx. 400 g each) per species, treatment, and replicate (72 sub-samples in total) were harvested at about 120° from each other by manual excavation

- The roots were cleaned from the soil on a sieve using tap water and processed for AMF colonization and molecular analyses.

- Percentage of mycorrhizal root length was determined on 5 g samples of fine roots (≤ 2 mm in diameter) after clearing and staining with 0.05% Trypan blue in lactic acid
- Genomic DNA was isolated from 250 mg of fine roots (≤ 2 mm in diameter)

- The AMF community composition was studied by PCR-DGGE, using a semi-nested PCR approach. A 550 bp fragment of the 18S rRNA gene was amplified by using the primer NS31 in combination with the primer AM1

TREE FUND
Cultivating Innovation

Urban Forestry & Urban Greening 83 (2023) 127916

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

ELSEVIER

Effects of pavements on diversity and activity of mycorrhizal symbionts associated with urban trees

Arianna Grassi[a,1], Irene Pagliarani[a,1], Caterina Cristani[a], Michela Palla[a], Alessio Fini[b], Sebastien Comin[b], Piero Frangi[c], Manuela Giovannetti[a], Alessandra Turrini[a,*], Monica Agnolucci[a,*]

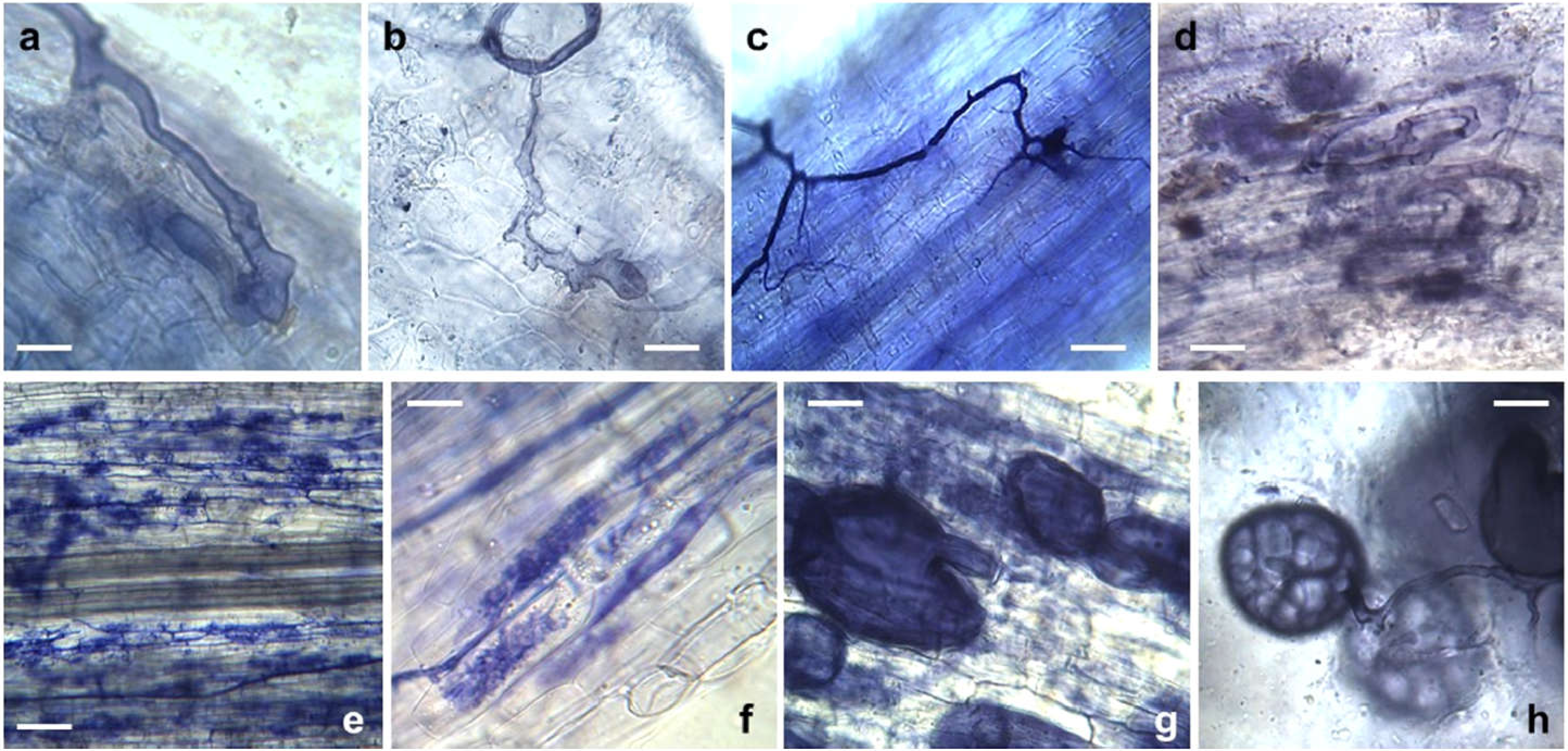
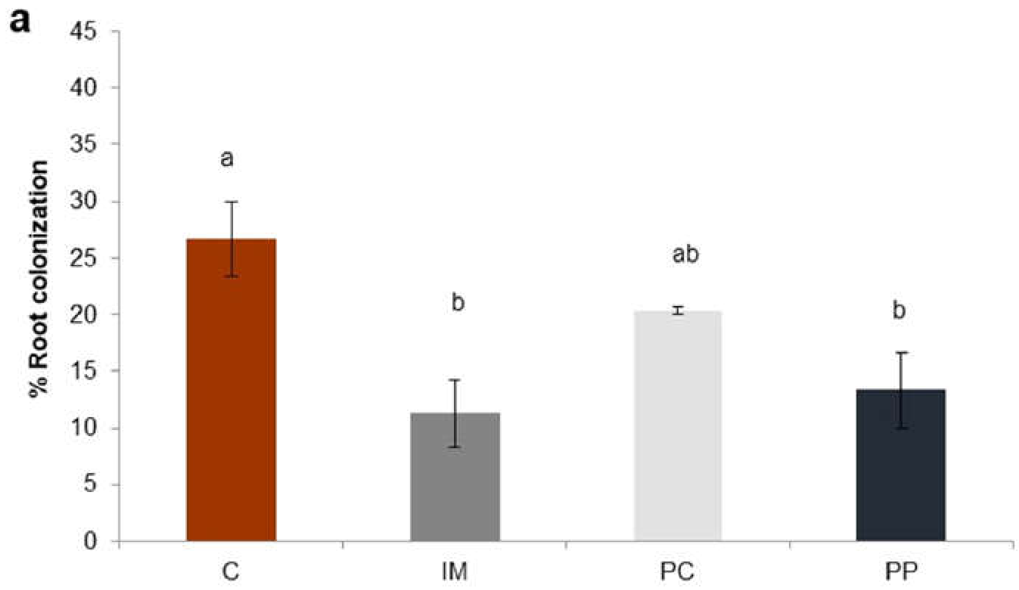


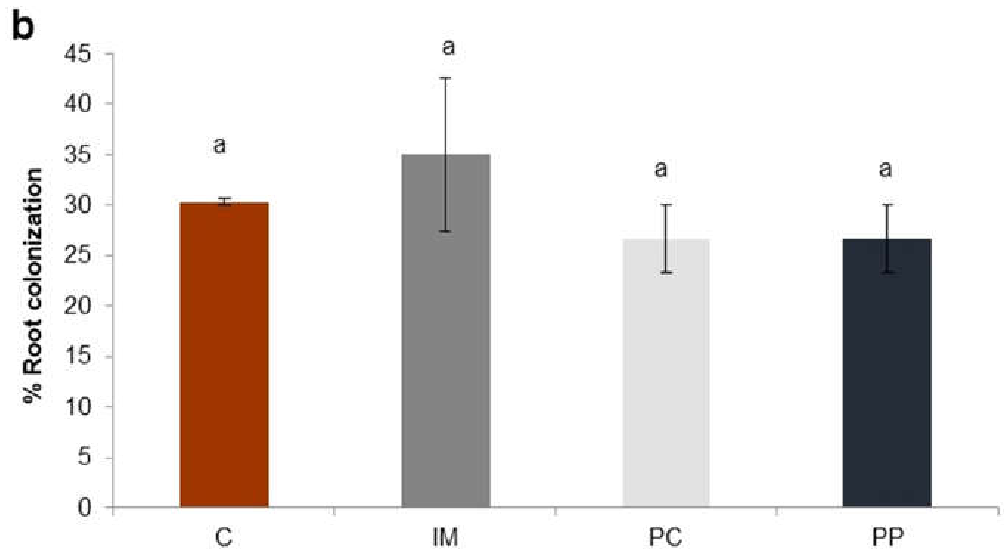
Fig. 2. Micrographs showing fungal structures characterizing the arbuscular mycorrhizal colonization of *Celtis australis* (a-d) and *Fraxinus ornus* (e-h) roots: (a), (c) entry points with appressoria, bar= 30 μm; bar= 65 μm, respectively; (b) empty appressorium, bar= 30 μm; (d) hyphal coils, bar= 30 μm; (e) root cortex colonized by intraradical hyphae and arbuscules, bar= 300 μm; (f) arbuscules, bar= 45 μm; (g) vescicles, bar= 45 μm; (h) spores, bar= 45 μm.

Root colonization

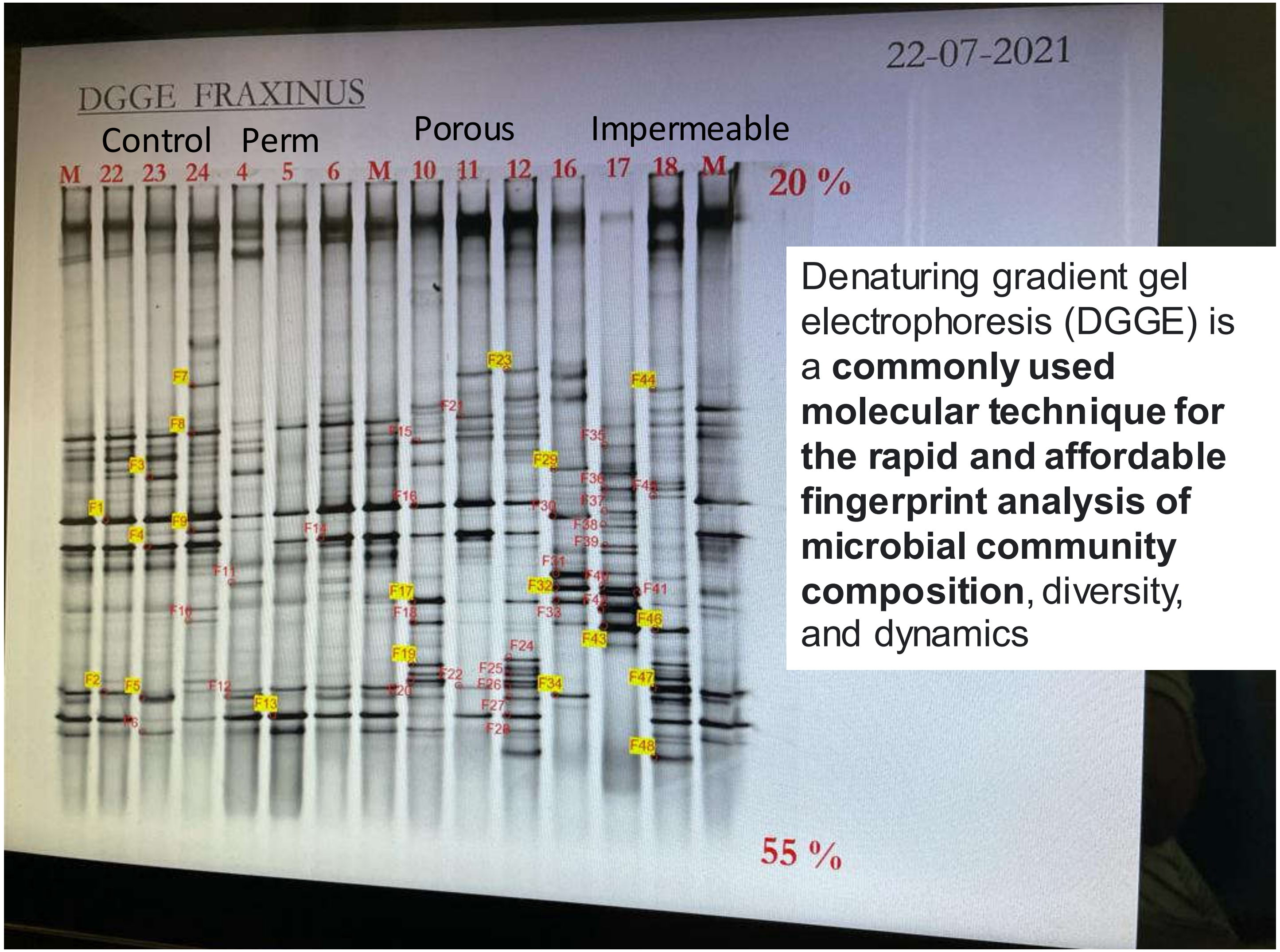
Histograms showing the percentage of root mycorrhizal colonization of *Celtis australis* (a) and *Fraxinus ornus* (b) growing in soil covered by impermeable pavements (IM), permeable pavers (PP), permeable concrete (PC) or left unpaved (C).



- All pavements except porous concrete reduced root colonization in *Celtis*, compared to control
- Pavements did not affect root colonization in *Fraxinus*

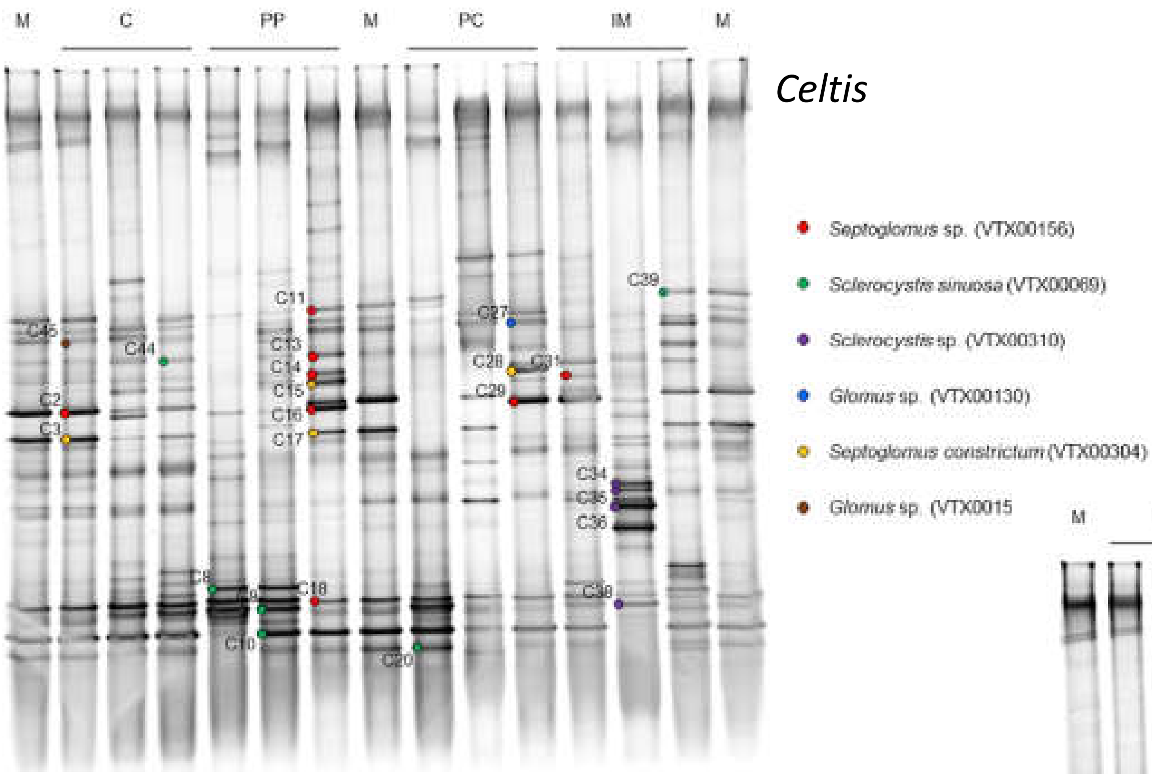


A matter of quality?

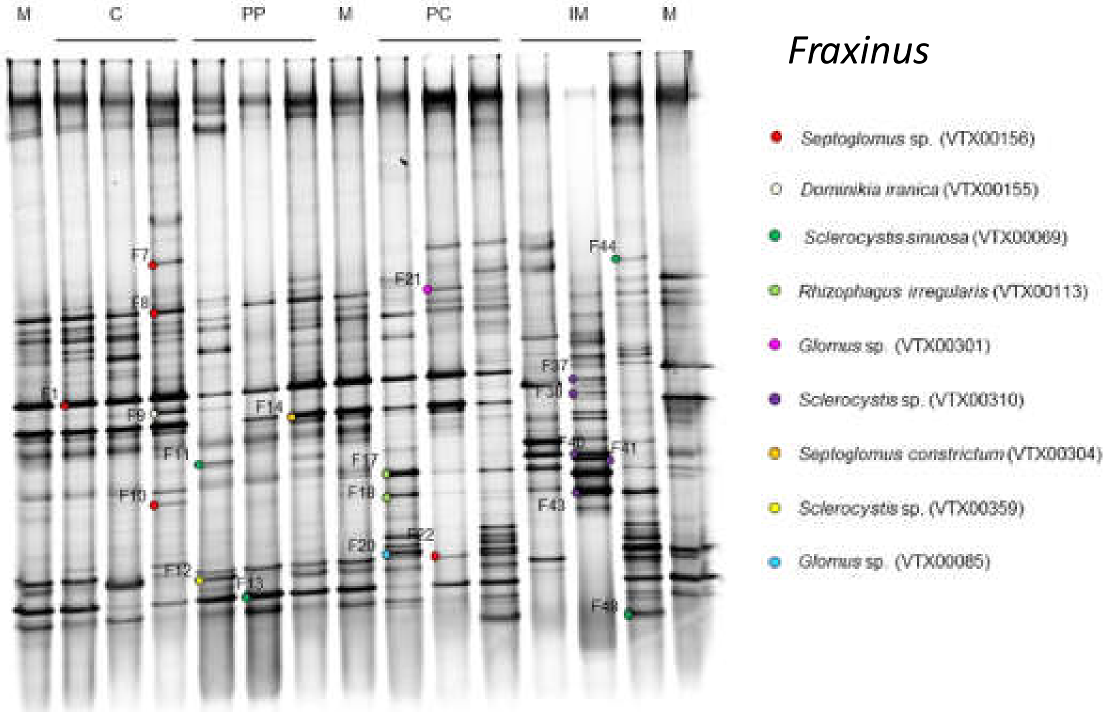


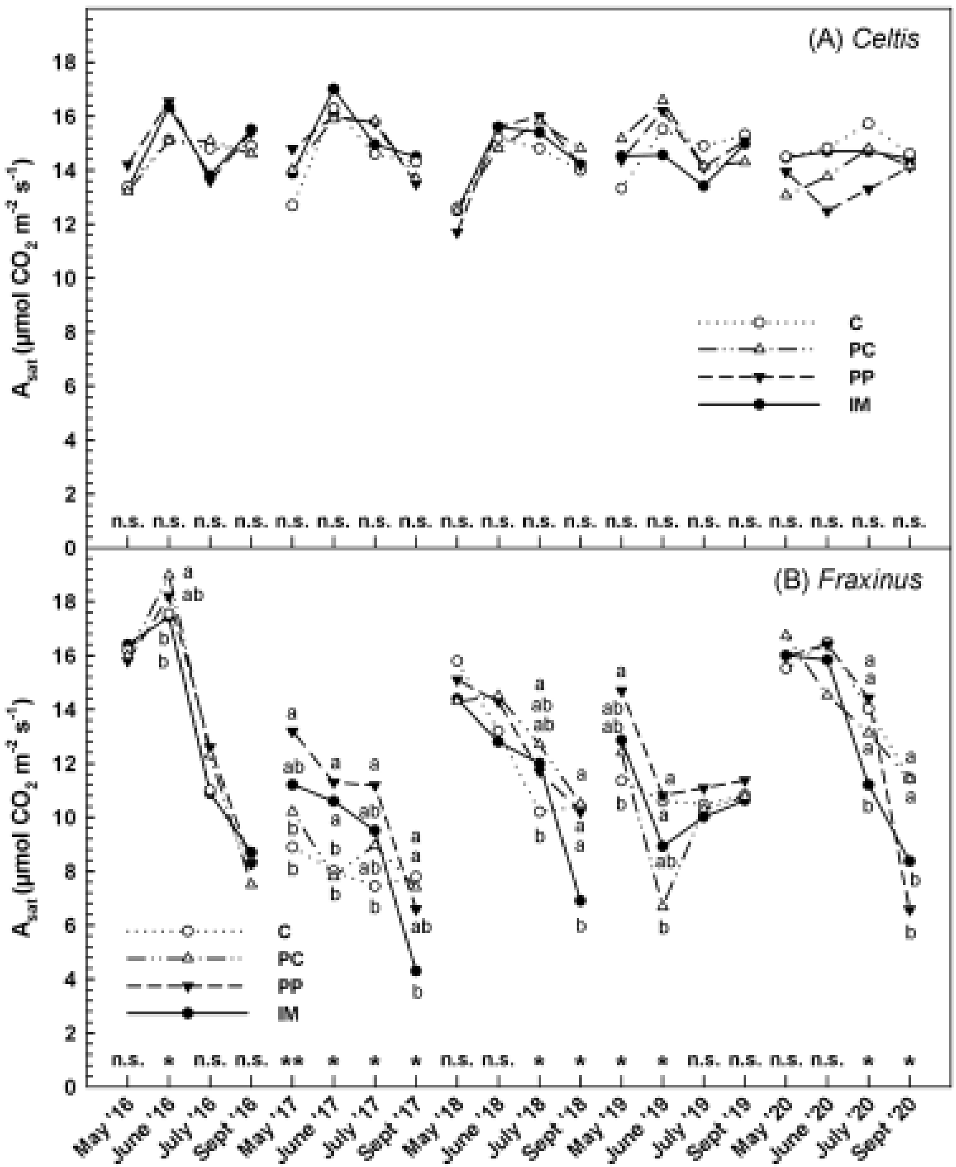
Denaturing gradient gel electrophoresis (DGGE) is a **commonly used molecular technique for the rapid and affordable fingerprint analysis of microbial community composition**, diversity, and dynamics

The predominant DGGE fragments originated sequences affiliated with the genera *Sclerocystis*, *Septoglomus* and uncultured *Glomus* in *C. australis*, and to *Sclerocystis*, *Septoglomus*, *Rhizoglomus*, *Dominikia* and uncultured *Glomus* in *F. ornus*



- In both plant species roots grown under impermeable pavements were characterized by an AMF community composition different from those of the other three treatments.
- In detail, in the impermeable pavements one species of the genus *Sclerocystis* (VTX00310) predominated in both plant species and the genus *Septoglomus* disappeared in *F. ornus*





Effects on plant health

- Net photosynthetic rate was unaffected by pavement treatment in *Celtis*
- In *Fraxinus*, impermeable pavements reduced A, compared to control, in 4 of the 20 measurements dates. This mostly occurred during early fall and occurred once in July 2020 (very wet year)

Effects on growth and ES

- Net CO_2 assimilation and latent heat disspation by the whole tree were estimated from A and LAI measurements using the big-leaf model
- CO_2 storage was calculated from DW, measured destructively
- Damage to pavements was estimated by dividing each plot into fifty 1x1 m squares, and visually assessing the amount of squared where the pavement was displaced or damaged in 2013 (root independent) and 2020 (root dependent).

Pavements

Pavements did not significantly affect tree health and above-ground growth over a 10-year period

+

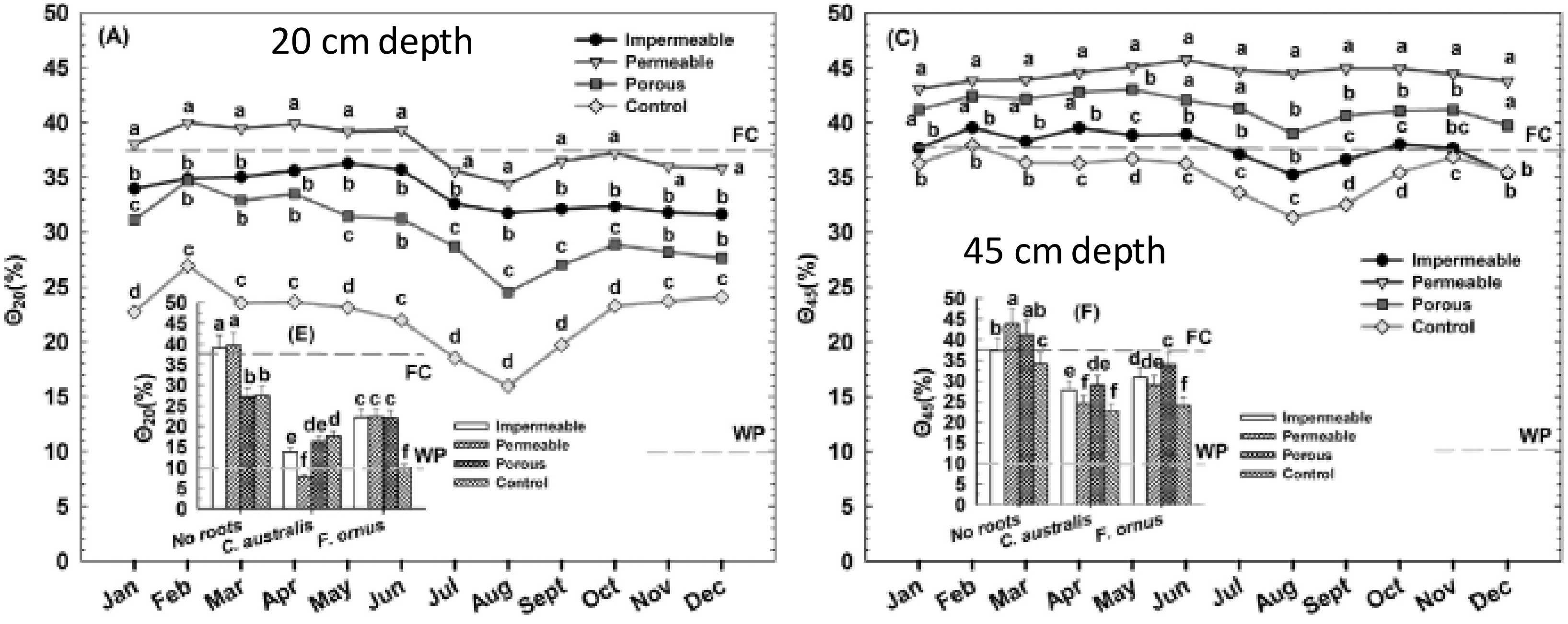
Both the structure of root system and the microbiota associated to roots are affected by pavement type

Which environmental factors did cause such changes?

Impermeable pavements were more durable than both porous and permeable pavements; the latter pavement is sensitive to displacement even with hard rooting species

Is there rationale for using permeable and porous pavements?

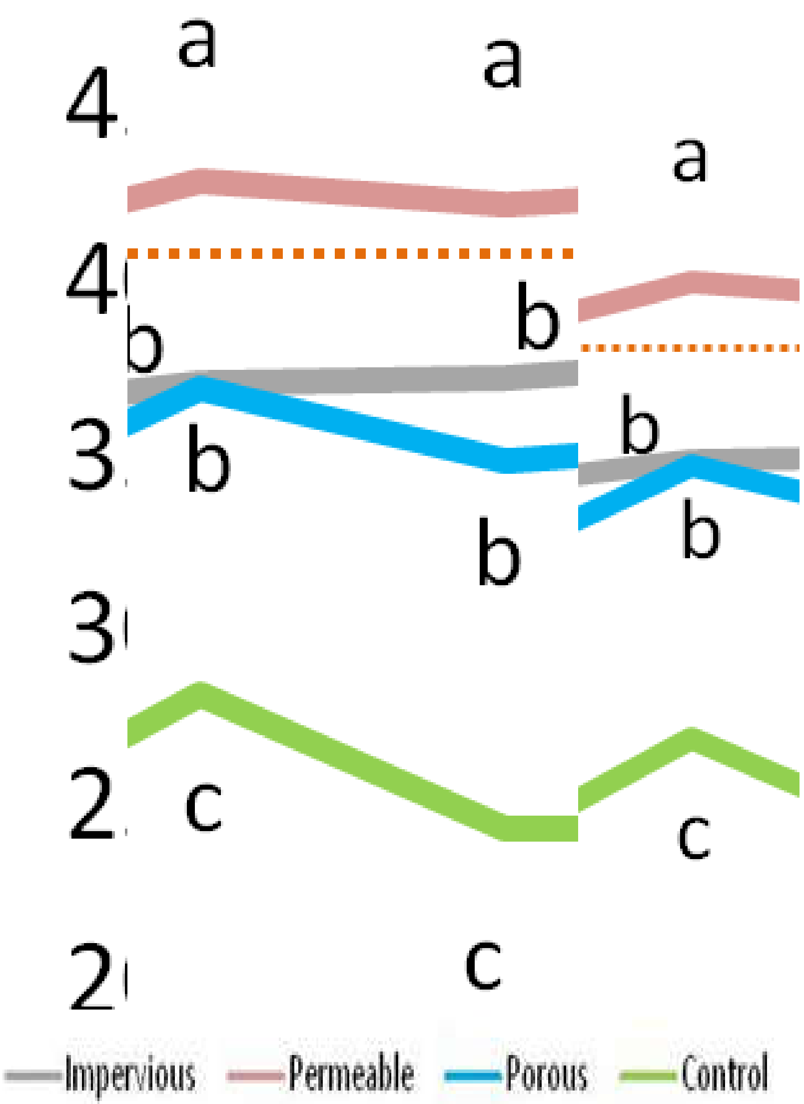
Volumetric soil moisture (2012-2015)



Fini et al., 2017, Env. Res.

Variation in moisture through the year:

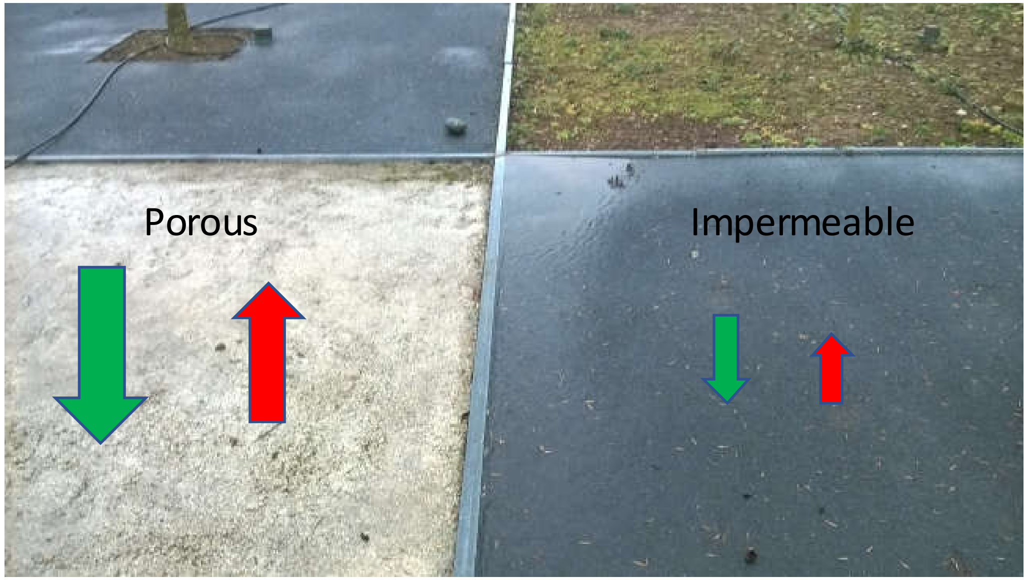
Asphalt: 8%
Permeable: 7%
Porous: 18%
Control: 29%

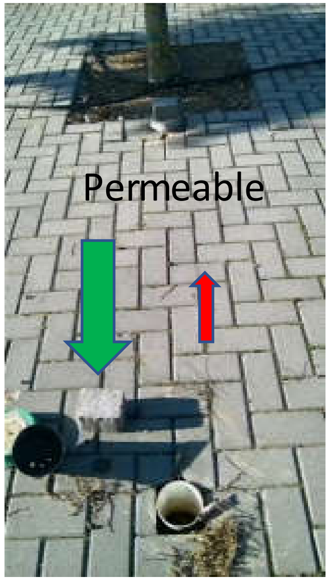


During soil rehydration, slope decreases with increasing pavament imperviousness

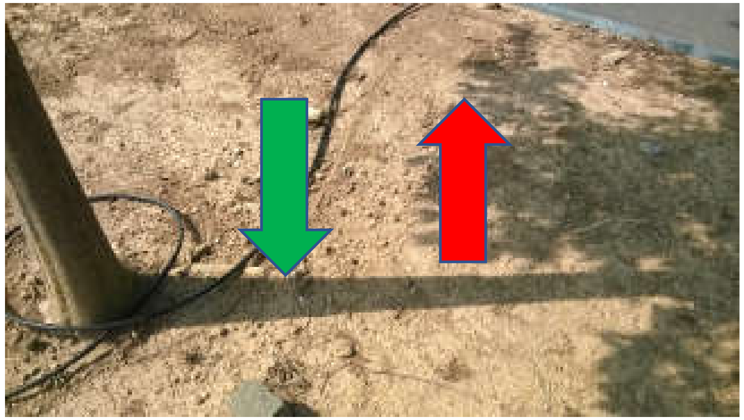
During soil dehydration, soils covered by impervious layers do not lose water as much as control

Soil moisture





Control



Denotes infiltration. Size is proportional to permeability

Denotes evaporation. Size is proportional to the amount of water that evaporates from soil

Impermeable pavements restrict water exchange
Permeable pavements allow infiltration (until clogging), but impair evaporation
Porous pavements mimic effectively water dynamics of bare soil

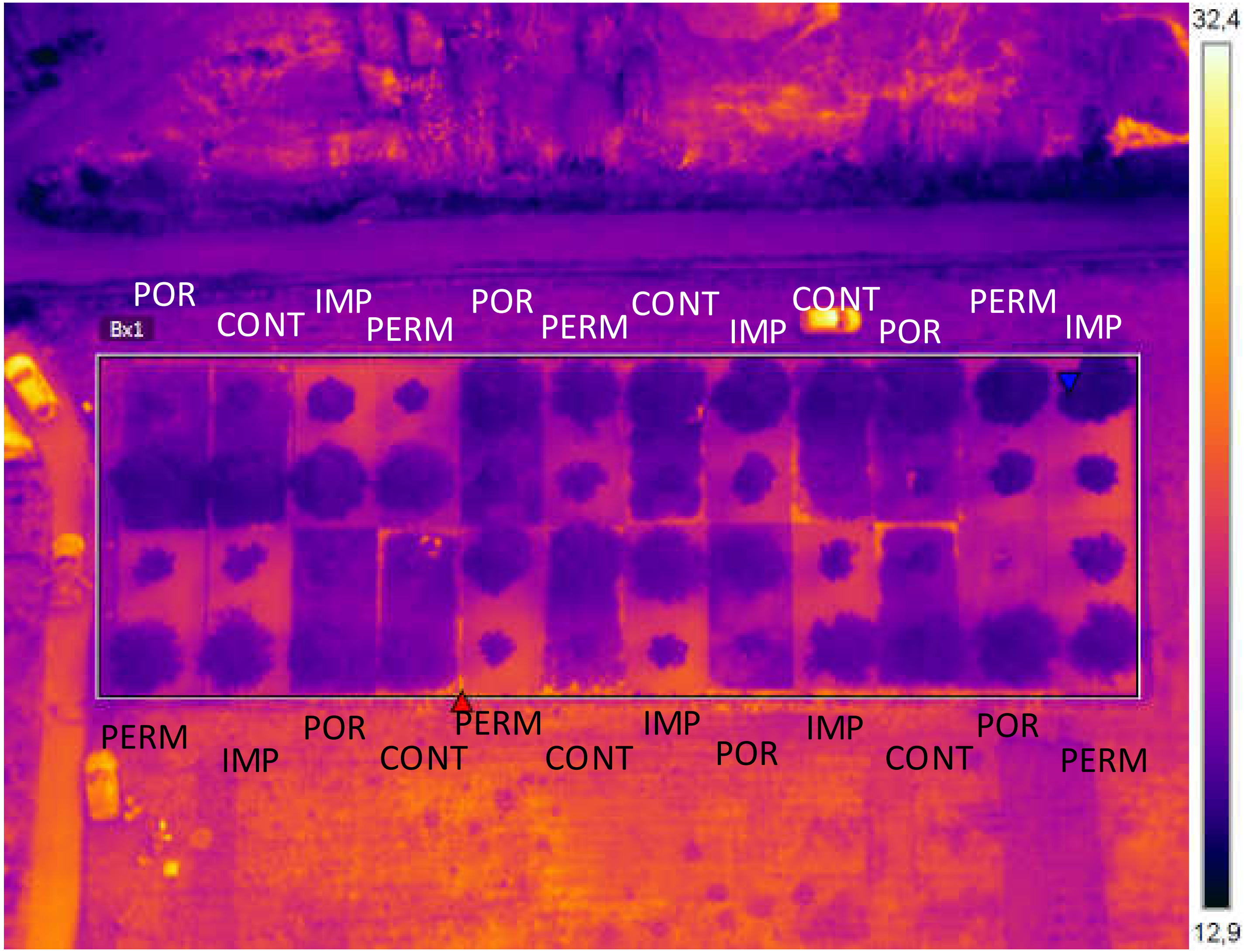
Surface temperature

Measured using a thermal camera mounted on an UAV in July 2018.

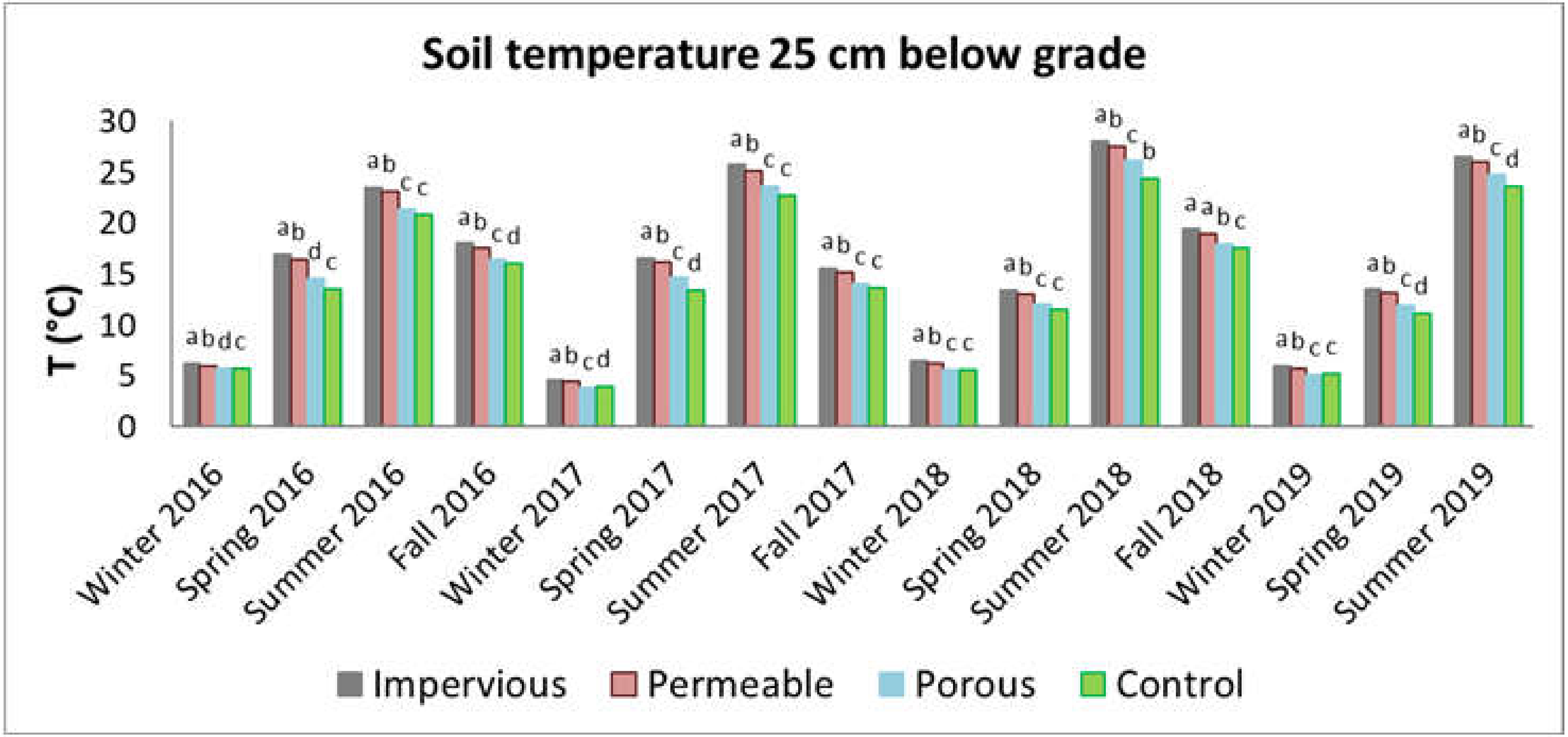
Soil temperature

Thermal camera highlighted warmer surface temperature in impermeable and permeable plots, compared to control and to porous.

UAV with thermal and multispectral camera flying on the pavements

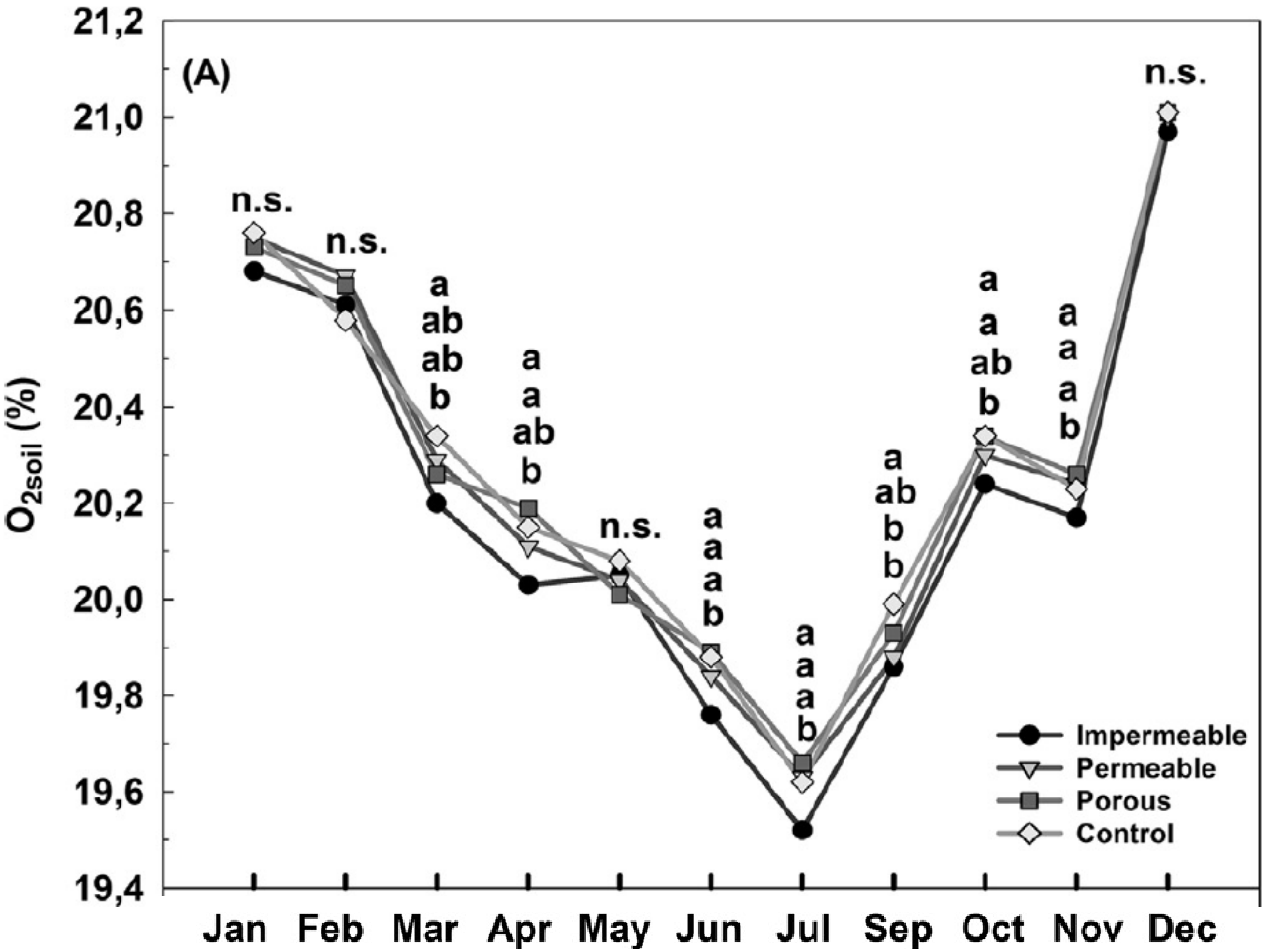


Soil temperature



The lack of evaporation from sealed soils increases soil T and triggers the “Subterranean UHI”. Also, higher soil temperature were hypothesized to affect root-associated mycrobiota

Soil oxygen content



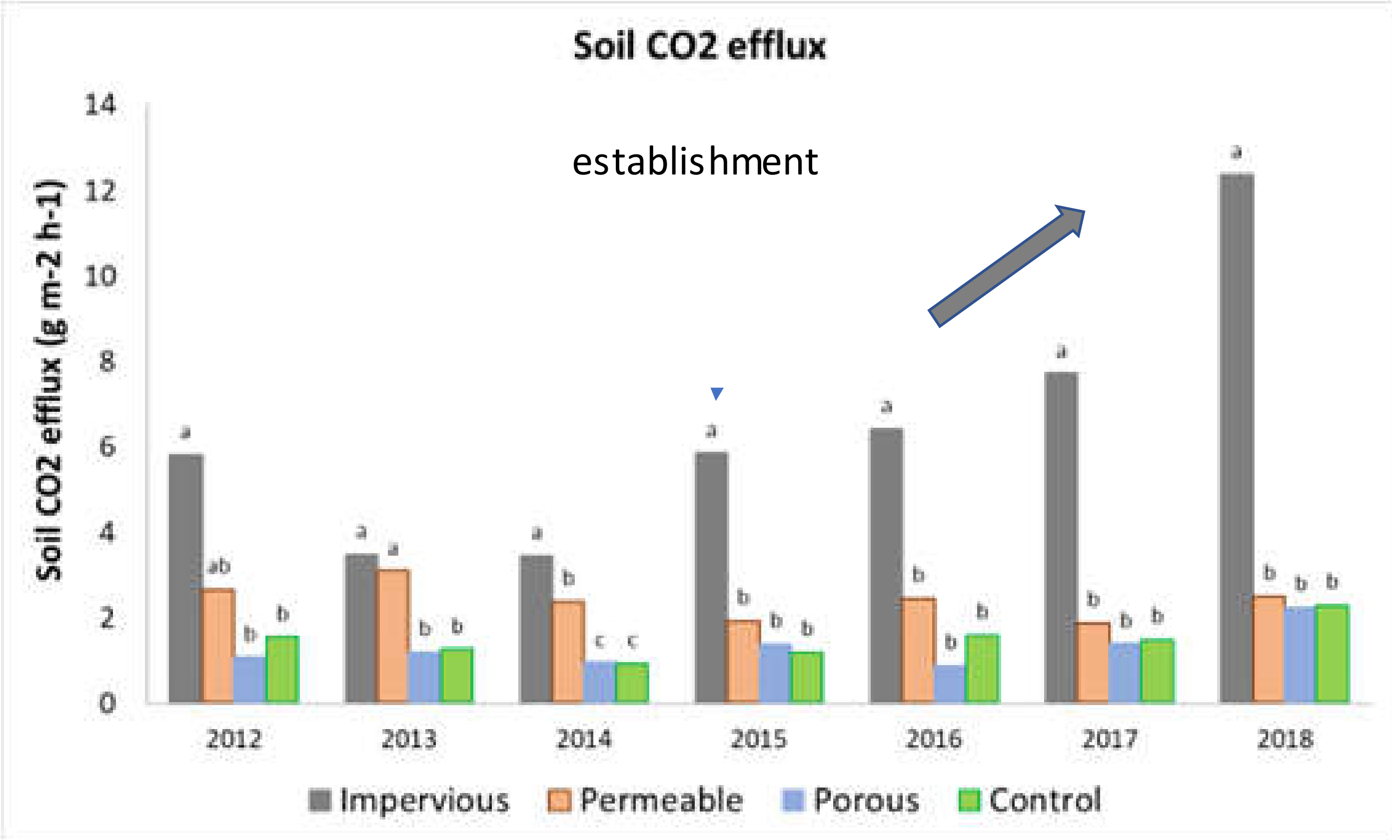
Soil O2 and soil CO2 efflux were measured using an oxygen probe associate to a soil respiration chamber connected to an infra-red gas analyser

It is unlikely that pavement-induced root hypoxia affected tree health

Soil CO_2

Impermeable and, to a lesser extent, permeable pavements, inhibited the diffusion of CO2 from soil to the atmosphere, resulting in substantial accumulation of CO2 in the soil.

Elevated-soil-CO_2 inhibits succinate dehydrogenase activity and depress root respiration, activity and growth (Burton et al., 1997; Sands et al., 2000)



Conclusions

- Although soil sealing affected moisture availability, because evapotranspirational losses are hardly recovered by rainfall infiltration, and root morphology, because fine root production was reduced by elevated soil CO2, we found no evidence that impermeable pavements promoted drought stress in trees
- A shift in the composition of root-associated AMF may have contributed to the “physiological acclimation” to sealed soils
- From the tree’s perspective, a high-quality soil matters much more than a pavement, but..
- The use of permeable pavements, however, should not be overlooked
- Both permeable and porous pavements are suitable for improving rainfall infiltration and reducing runoff in urban sites, but only porous pavements allows the evaporative coolingneeded for urban heat island mitigation

Support arboriculture research
with a donation to the TREE Fund

Healthy trees are rooted in research!

Donate now at www.treefund.org

Thank you for your attention

TREE FUND

The Research & Education Endowment Fund

110000 dollars funding

RegioneLombardia

Research was co-funded by TREE Fund's projects Jack Kimmel and Research fellowship, and by Regione Lombardia, project METAVERDE (2010-2012)