Trees in paved sites

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The Anthropocene Era

We live in an Era when 60% of population lives in cities. Although cities occupy only 3% of World's surface, they use up to 80% of resources and produce about 75% of emissions.

2

Population vs. urbanized land change 1982-1997

USA zone	Change in population %	Change in urbanised land %
Midwest	7.1	32
Northeast	6.9	39
South	22.2	59
West	32.2	48
United States	17.0	47

Da Benedict&Mahon, 2002

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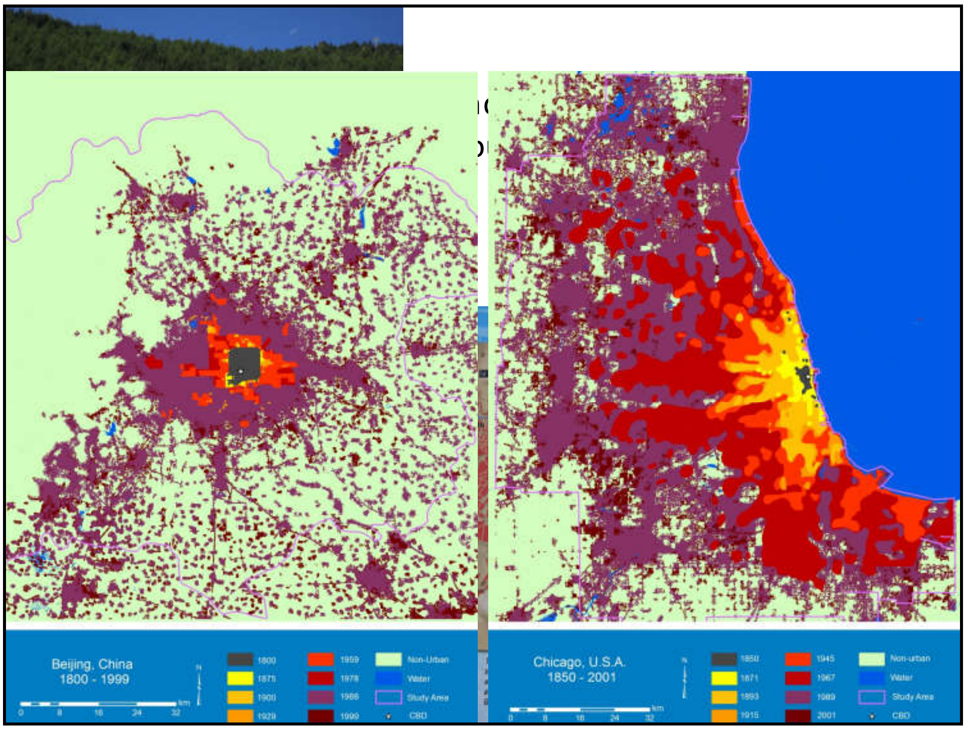

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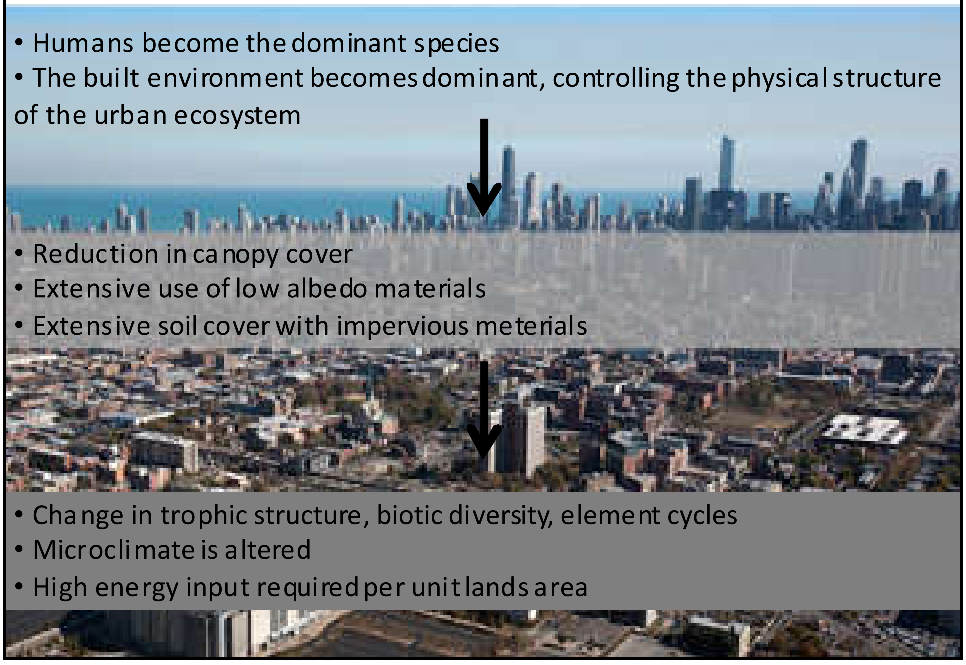
What does urbanization mean?



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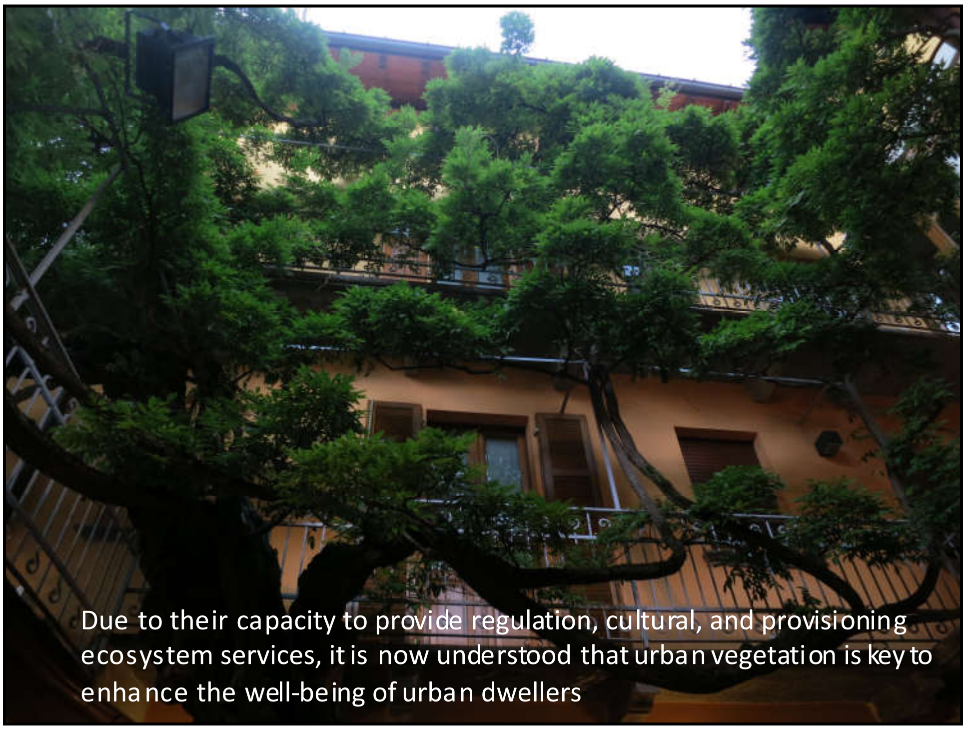

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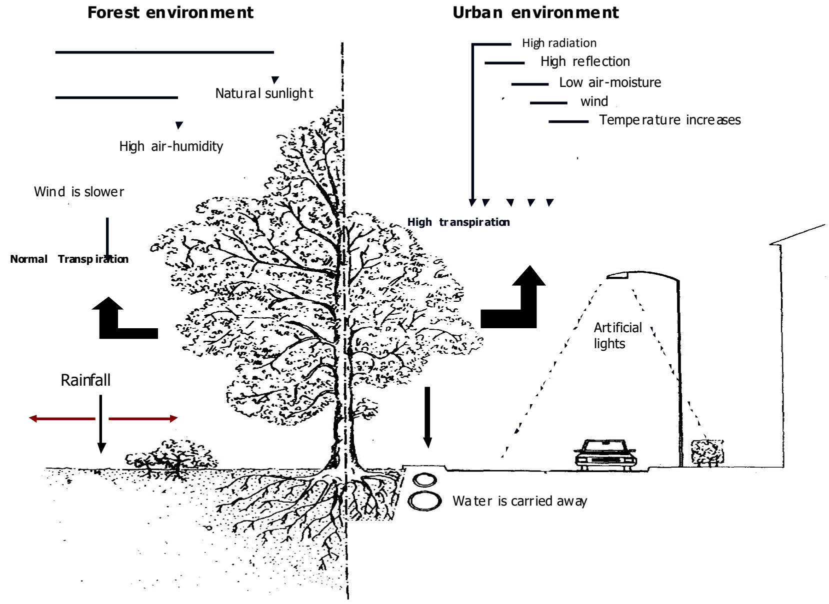
Growing conditions largely differ between urban and forest sites



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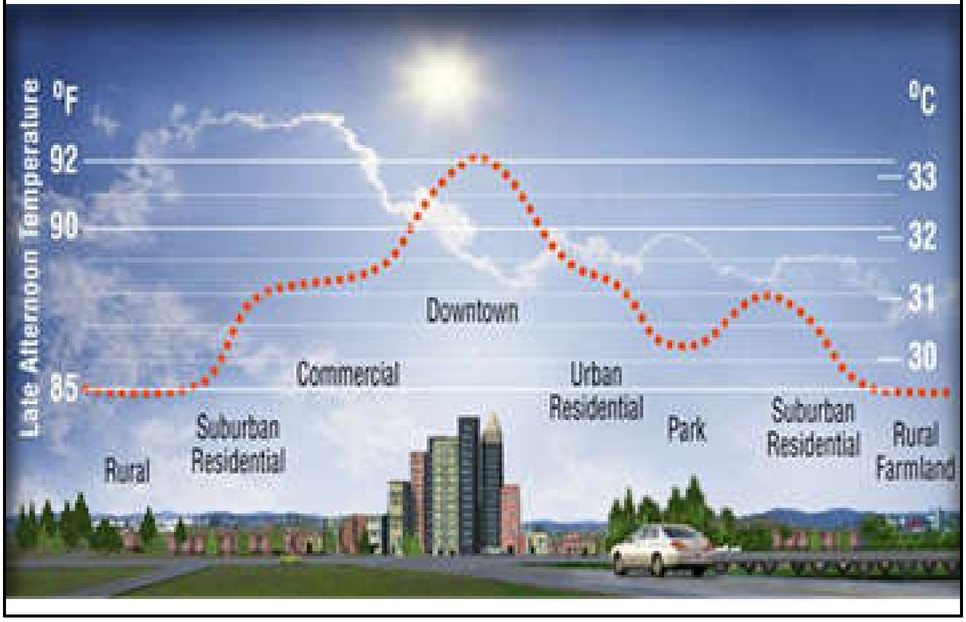
Urban heat island



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Consequences of urbanization: soil sealing and Urban Heat Island

In the United States it is estimated that 3 to 8% of the electricity demand is used to compensate for the effect of "heat island"

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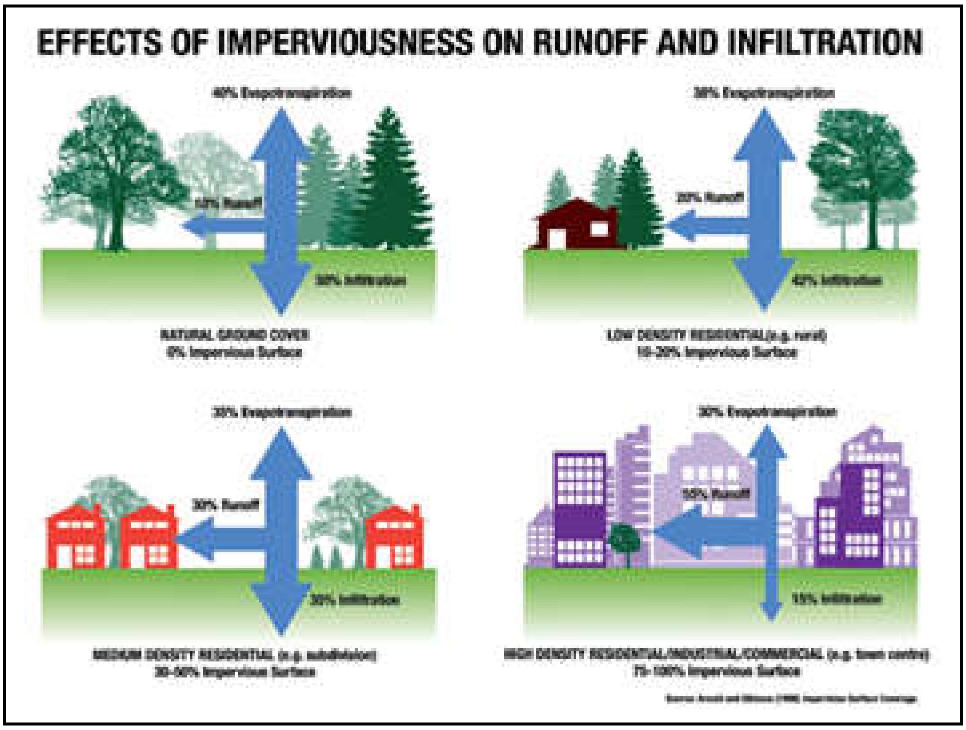
EFFECTS OF IMPERVIOUSNESS ON RUNOFF AND INFILTRATION
40% Evapotranspiration
10% Runoff
50% Infiltration
NATURAL GROUND COVER
0% Impervious Surface
38% Evapotranspiration
20% Runoff
42% Infiltration
LOW DENSITY RESIDENTIAL(e.g. rural)
10-20% Impervious Surface
35% Evapotranspiration
30% Runoff
35% Infiltration
MEDIUM DENSITY RESIDENTIAL (e.g. subdivision)
35-50% Impervious Surface
30% Evapotranspiration
55% Runoff
15% Infiltration
HIGH DENSITY RESIDENTIAL/INDUSTRIAL/COMMERCIAL (e.g. town centre)
75-100% Impervious Surface

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In environments like this, less than 15% of
rainwater can infiltrate in the soil;
85% is runoff

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FREQUENCY OF EXTEME EVENTS IS INCREASING DUE TO CLIMATE CHANGE. THERE IS AN URGENT NEED TO MITIGATE THE DELETERIOUS EFFECTS OF SOIL SEALING

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

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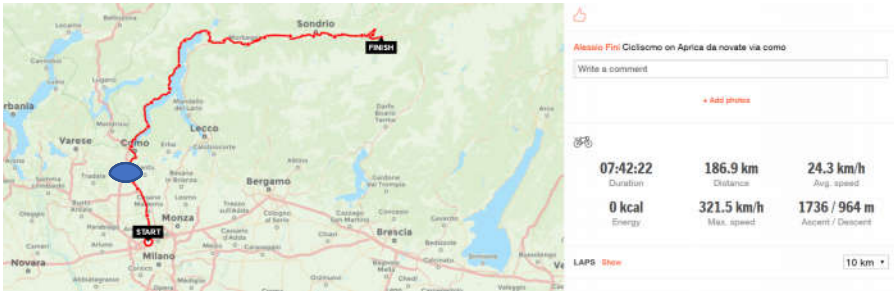
The first stage stopped for a while in Vertemate con Minoprio (after just 20 km).
Something was going to start there..



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

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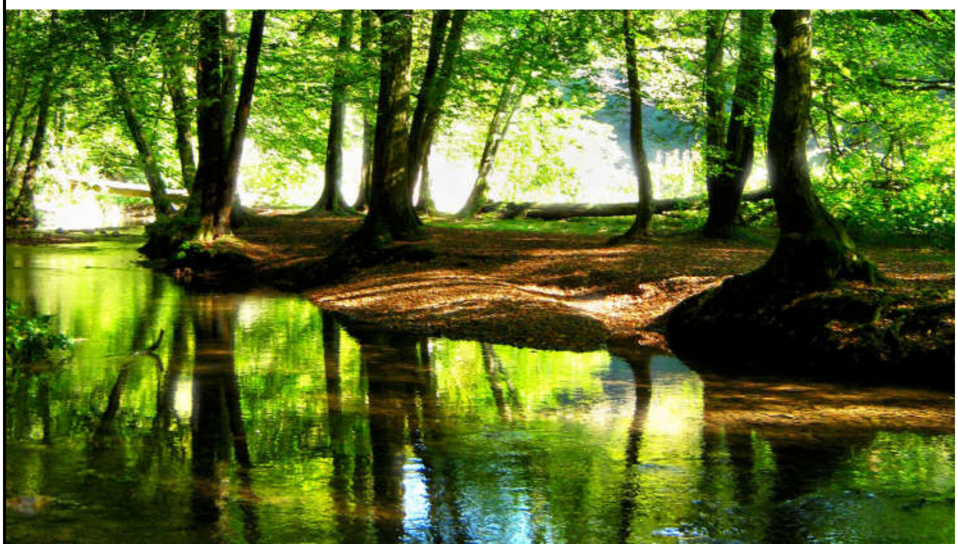

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On a sandy-silt..

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

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In 2011, an experimental field with 24 plots was built

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Four soil treatments were imposed, with 6 replicates each arranged according to a randomized complete block design. Pavement thickness was about 15 cm in all pavements

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)

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Alternatives to impermeable pavements

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

These pavements have infiltration coefficients = 0.5-0.7, compared to 0.15 of asphalt

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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

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- *Fraxinus* is an **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

- *Celtis* is an **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

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How the field looked like in March 2012

Monitored for 9 years after transplant
Aim: test the effect of pavements on:

EXP 1: establishing trees

EXP 2: established trees

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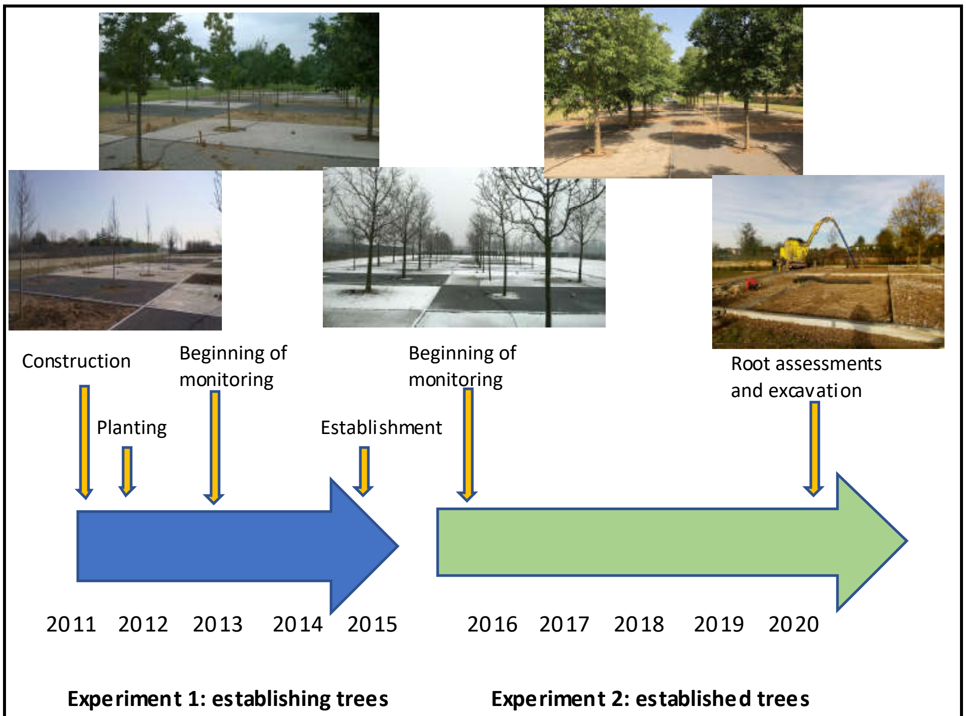

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Experiment 1 - Hypotheses:

Reduction of infiltration and soil moisture

↓

Drought stress

Reduction of gas exchange between soil and atmosphere

↓

Root hypoxia

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Measurements: soil traits

- Soil moisture (v/v), measured weekly at 20 cm (5 cm below sub-grade) and 45 cm (30 cm below sub-grade) depth, measured with FDR soil moisture probes
- Soil temperature, measured monthly at 25 cm depth using a temperature probe
- Soil oxygen content and soil CO_2 efflux, measured monthly using a soil respiration chamber

These parameters were measured both in the paved soil next to the planting pits and in the paved soil in the middle of the paved plot, not colonized by roots yet.

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Measurements: plant traits

GROWTH:

• Shoot growth (10 shoots per plant), measured at the end of the growing season in 2012, 2013, and 2014

• DBH, measured at the end of the growing season in 2012, 2013, and 2014

PHYSIOLOGY:

• Leaf gas exchange (photosynthesis and transpiration) measured monthly during the growing season on 12 leaves per treatment and species using a IRGA

•Fv/Fm, measured on the same leaves as gas exchange using a portable fluorometer

• Pre-dawn and midday water potentials, measured using a Scholander-type pressure bomb

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2012-2020: Chlorophyll fluorescence

Chlorophyll fluorescence: Fv/Fm was measured on leaves acclimated to darkness for 40 minutes using a leaf clip.

Healthy plants: Fv/Fm > 0,8

Mild stress: Fv/Fm tra 0,75 e 0,8

Moderate stress: Fv/Fm tra 0,75 e 0,7

Severe stress: Fv/Fm tra 0,6 e 0,7

Sub-lethal stress, visible signs of chlorosys: Fv/Fm < 0,6

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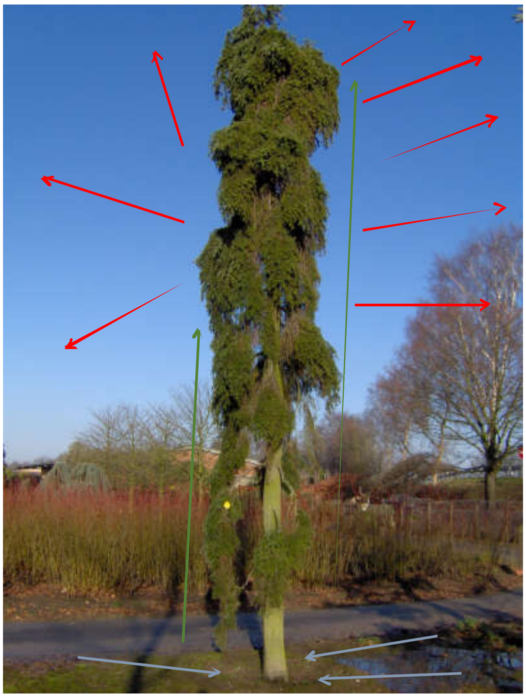

Ψ (Water potential)

$\Psi_{air} < \Psi_{leaf} < \Psi_{xilem} < \Psi_{roots} < \Psi_{soil}$

When Ψ_{soil} decreases (i.e. because of drought), plant water potential must also decline, if the plant want to absorb water

Excessive decline in root, xilem and leaf water potentials may lead to hydraulic deterioration because of cavitation and embolism

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2013-2020: water potential

Pre-dawn water potential:

It is measured at the end of the night, after a long time without transpiration because of darkness. Thus, all plant organs reach the equilibrium and water potential of the leaf is representative of the water status of the whole plant

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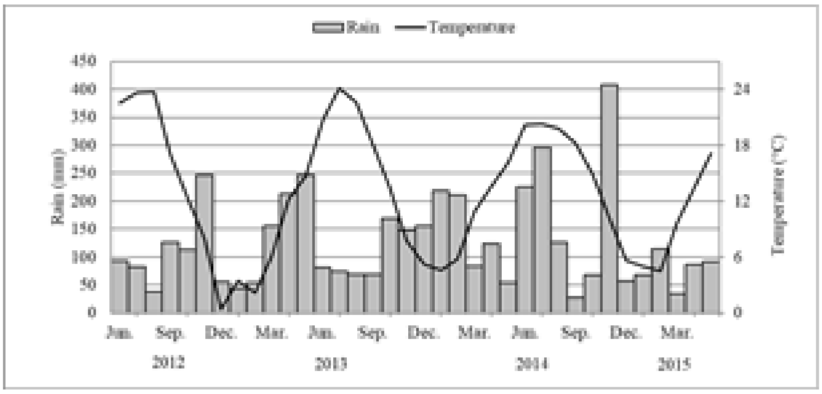
Total rain: 1259 mm

Total rain: 1480 mm

Total rain: 1899 mm

Total rain: 993 mm



Year	Avg 2012-2019	Avg 1981-2011
Temperature (°C)	13,3	13,3
Rainfall (mm)	1284	1106

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Experiment 1: results (2012-2015)

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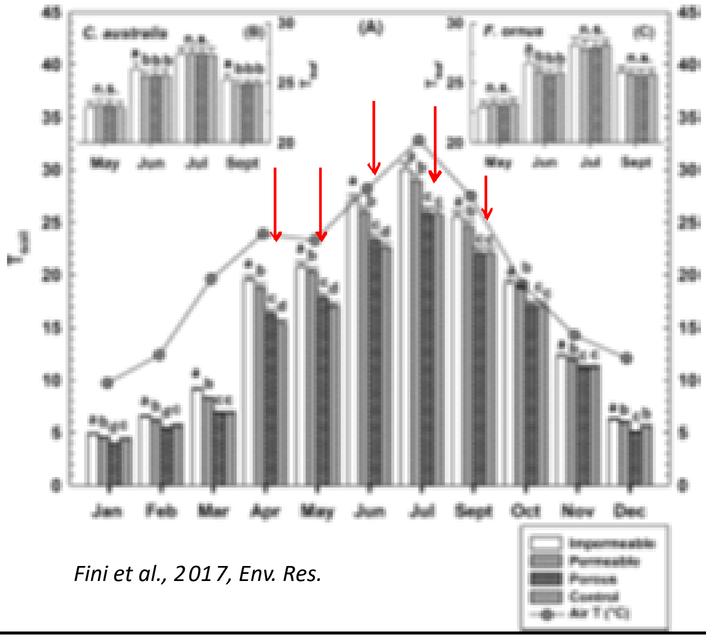
Effects on soil - Temperature



Fini et al., 2017, Env. Res.

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Causes: Albedo?

Albedo of the different pavemnts (measured using coupled spectroradiometers)

Impermeable = 0,11
Permeable = 0,16
Porous = 0,26
Control = 0,16

Control and permeable pavements have the same albedo, but strikingly different soil temperatures

Albedo poorly explains temperature differences

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Causes: soil moisture?

20 cm
deep

45 cm
deep

Frequency domain reflectometry (FDR)
moisture probes

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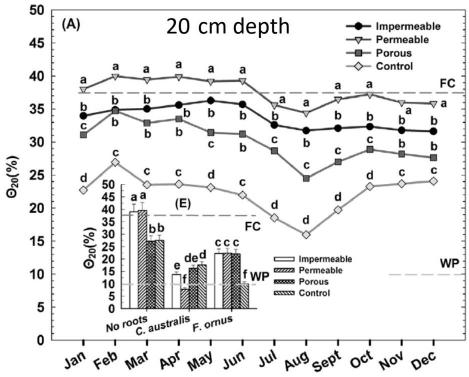
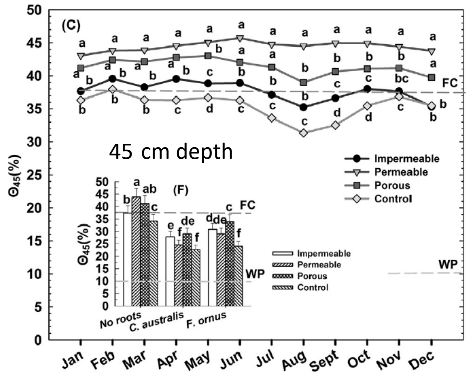
Volumetric soil moisture (2012-2015)





Fini et al., 2017, Env. Res.

Variation in moisture through the year:

Pavements did not decrease soil moisture availability in young trees

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

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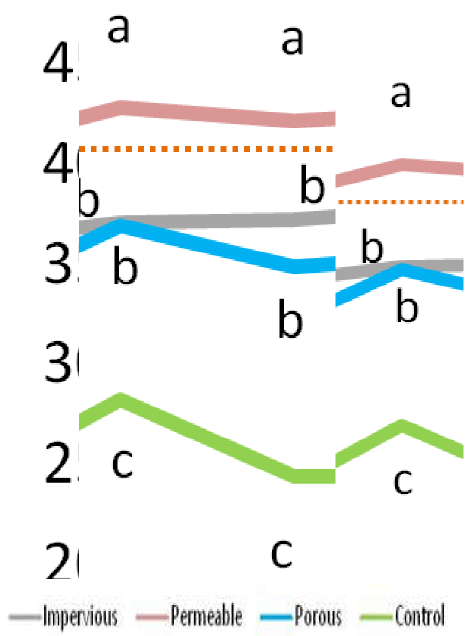

During soil rehydration, slope decreases with increasing pavament imperviousness

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

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Take home message - Soil moisture

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

Water evaporation converts sensible heat in latent heat: 1 gram of water dissipates 2272 J

Reduction of evaporation from shallow soil layers because of soil sealing may be a major determinant of soil warming and urban heat island

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Surface temperature

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

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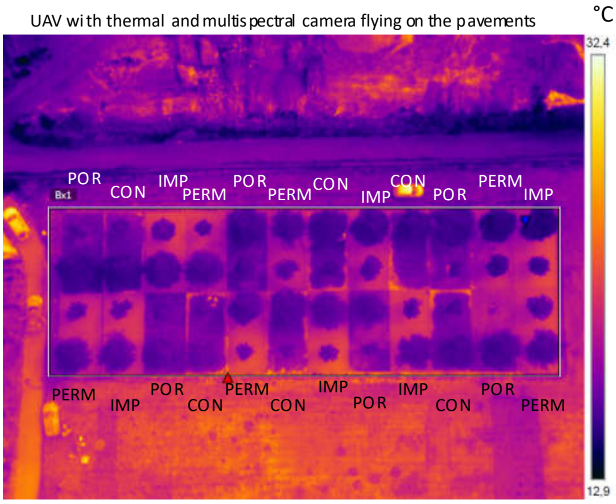
Surface temperature

Warming due to reduced evaporation by impermeable and permeable pavements

UAV with thermal and multispectral camera flying on the pavements



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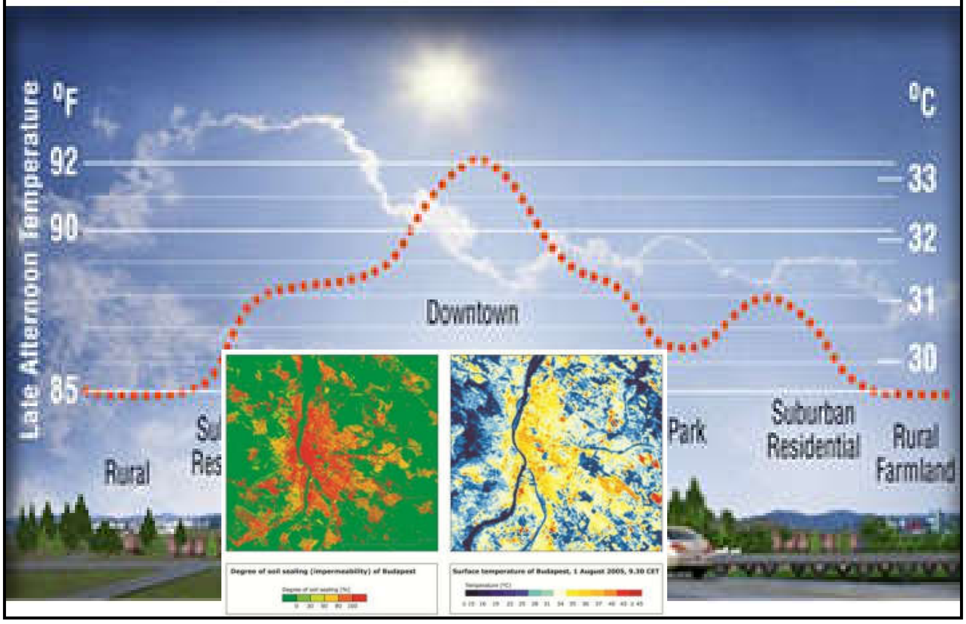
The urban heat island effect



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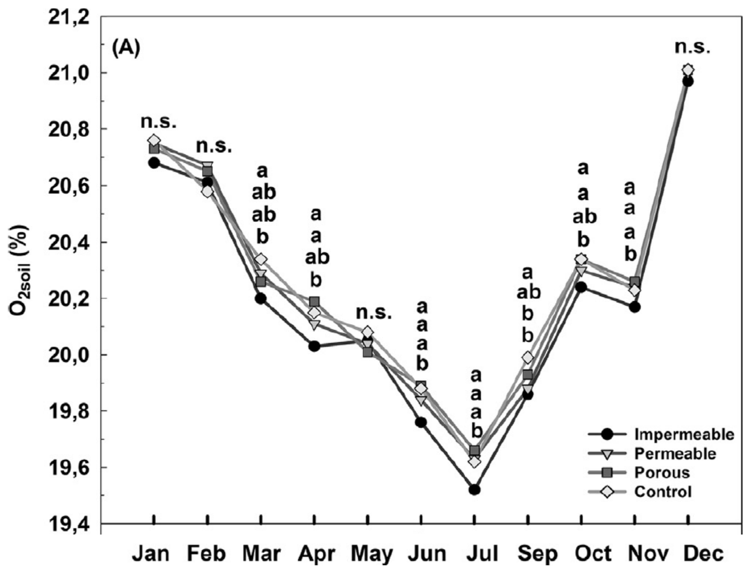
Soil oxygen content (2012-2015)



It is unlikely that hypoxia affected tree health (hypothesis 2 can be discarded for young trees)

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Effects on soil – soil CO_2

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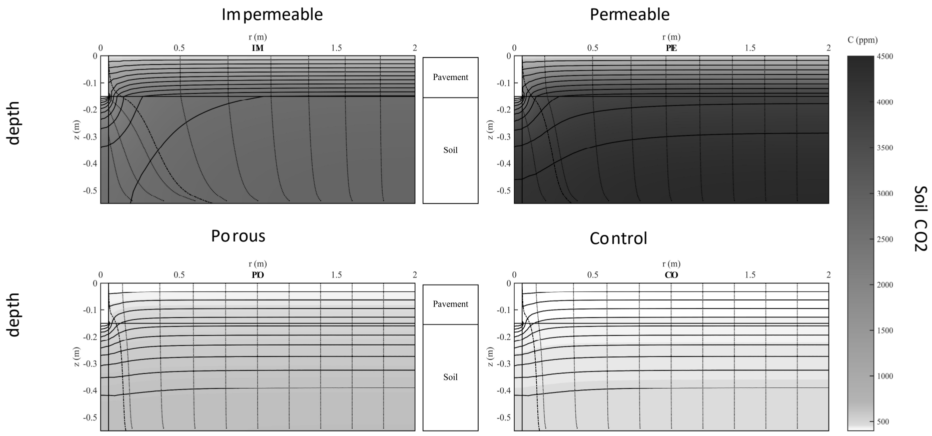
Effects on soil - **Soil CO_2** (2012-2015)



Soil CO2 concentration was up to 10-fold higher under impermeable and permeable pavements than porous and control

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Potential effects of soil CO_2 accumulation

- Inhibition of root respiration and root activity
- Reduction of root growth
- pH of root cells decreases

Reversible
3000 – 4000 ppm

Irreversible
Over 10000 ppm

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So…

Trees in paved sites experienced:

- Higher soil temperature (except for porous)
- Higher soil moisture
- Higher soil CO2 concentration (except for porous)
- Similar O2 (except for impermeable)

Compared to control.

Consequences for trees?

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Tree growth was not affected by pavements (2012-2015)

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

Fini et al., 2017

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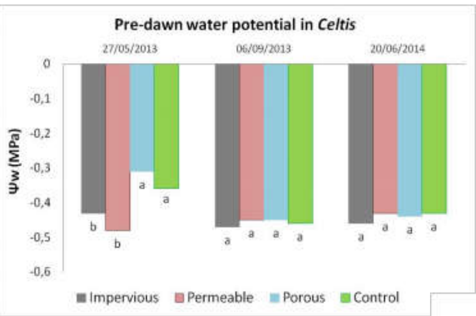
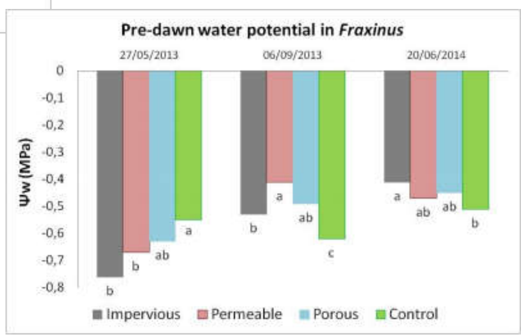
Effects on trees – water relations



Pre-dawn water potential is well representative of plant water status, because, in the absence of transpiration, water potential equilibrates among plant organ and with the soil



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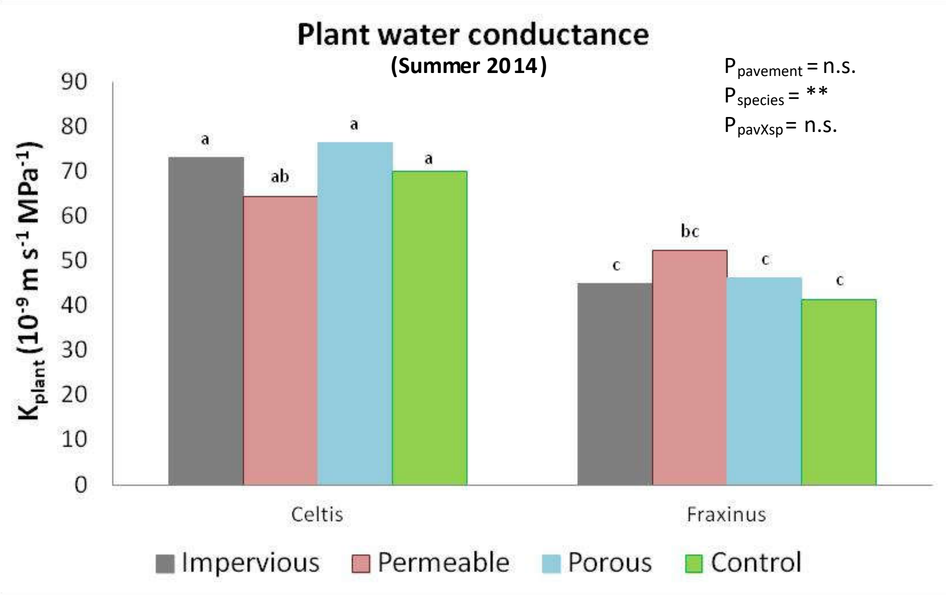
$K_{plant} = E/(\Psi_{predawn} - \Psi_{midday})$



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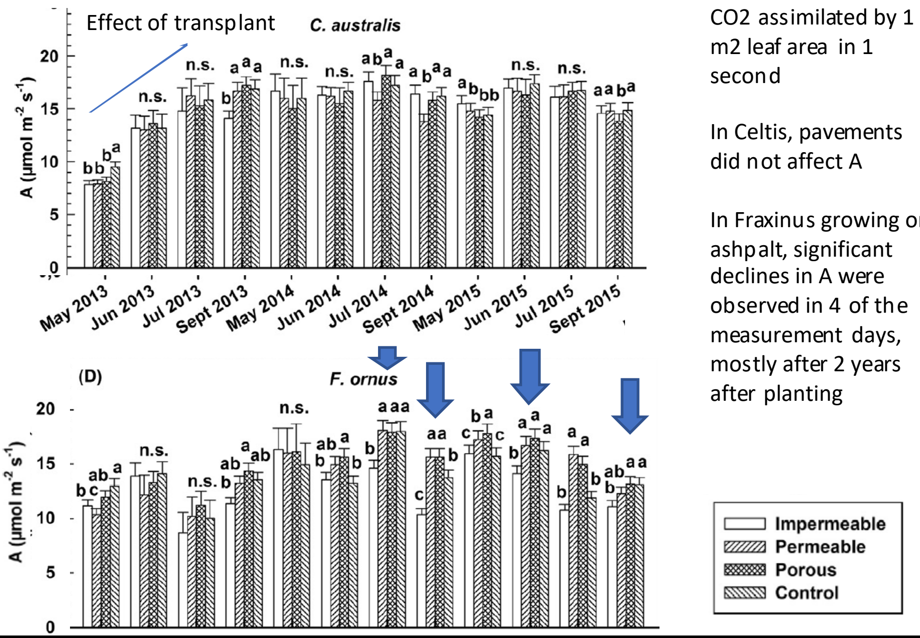
Net photosynthesis



It is the amount of CO2 assimilated by 1 m2 leaf area in 1 second

In Celtis, pavements did not affect A

In Fraxinus growing on ashpalt, significant declines in A were observed in 4 of the measurement days, mostly after 2 years after planting

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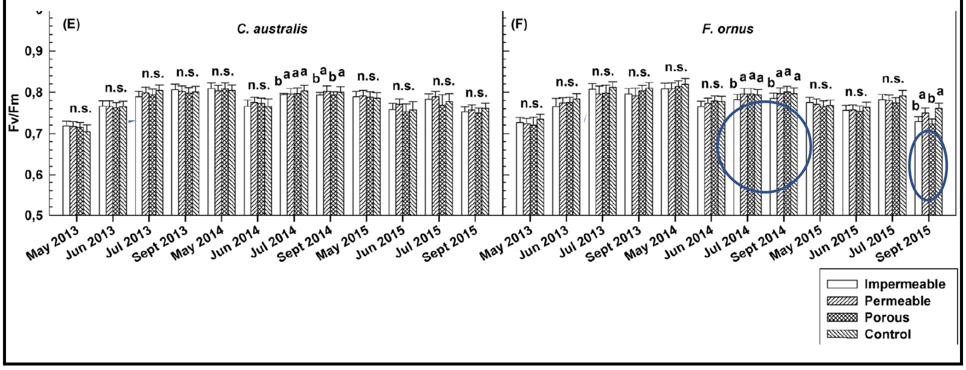
Evidence for metabolic stress on PSII?

Fv/Fm	Plant health
> 0,80	Healthy
0,70 – 0,80	Mild/moderate stress
< 0,7	Severe stresse

- No evidence of photoinhibition in hackberry
- Some in ashes growing in the impervious treatment, but only very mild stress and in the last two samplings



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Conclusions – Effects on establishing trees

- Planting trees in paved soils is essential to maintain evapotranspiration in urban areas
- Pavements had limited effects on growth and physiology of newly planted trees
- *Celtis* is very tolerant to all types of soil cover, during establishment
- *Fraxinus* in impervious pavements displayed some signs of (very mild) stress since the third year from planting


Environmental Research 156 (2017) 443–454

Contents lists available at ScienceDirect

Environmental Research

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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]

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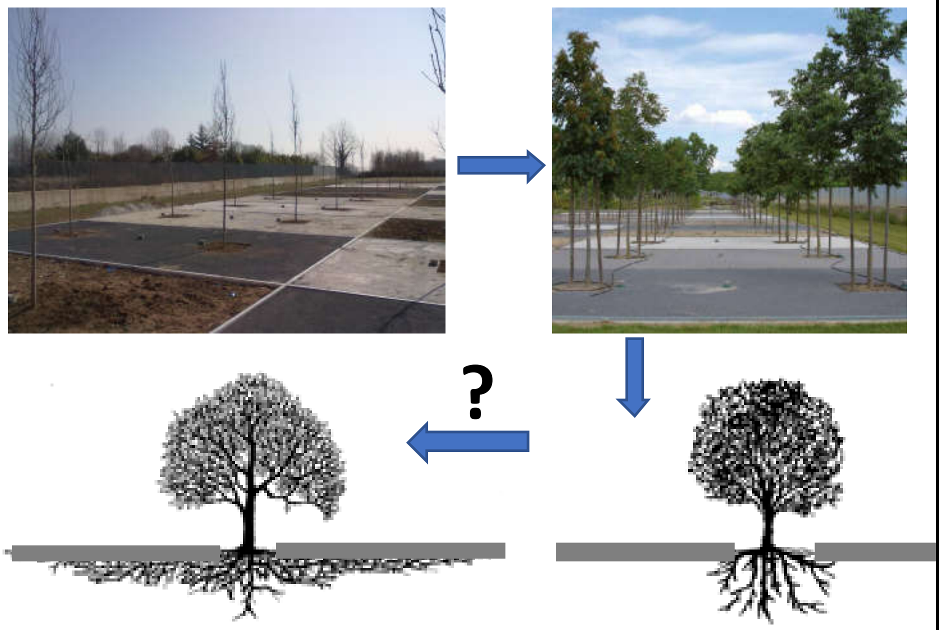
Limitations



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Esperimento 1: thanks to

TREE FUND
Tree Research & Education Endowment Fund

Jack Kimmel Award

RegioneLombardia

Progetto METAVERDE

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Fall 2015, while we were enjoying the ISA conference al Gaylord Hotel in Florida…

… trees fully established in the pavement field

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Experiment 2: established trees (2016-2020)

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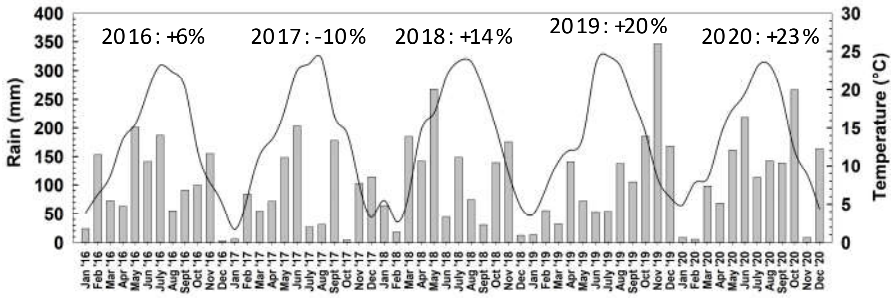
Weather conditions (2016-2020)



Average 30-year rainfall (1990-2020): 1186 mm

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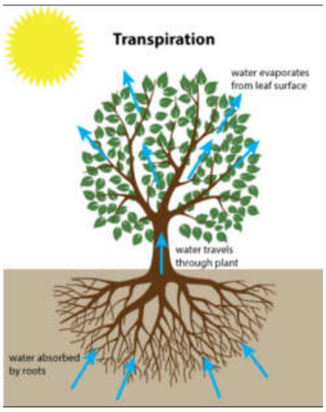
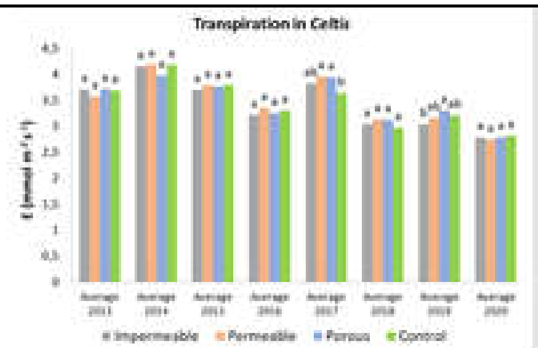
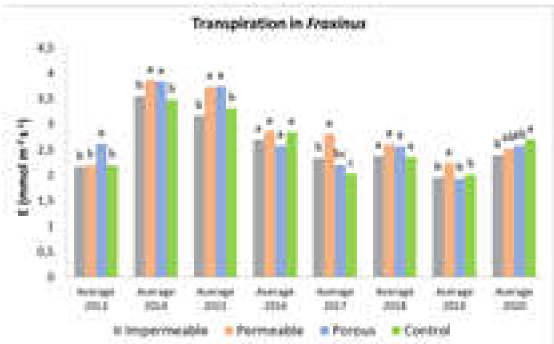
Traspiration per unit leaf area did not change much over time







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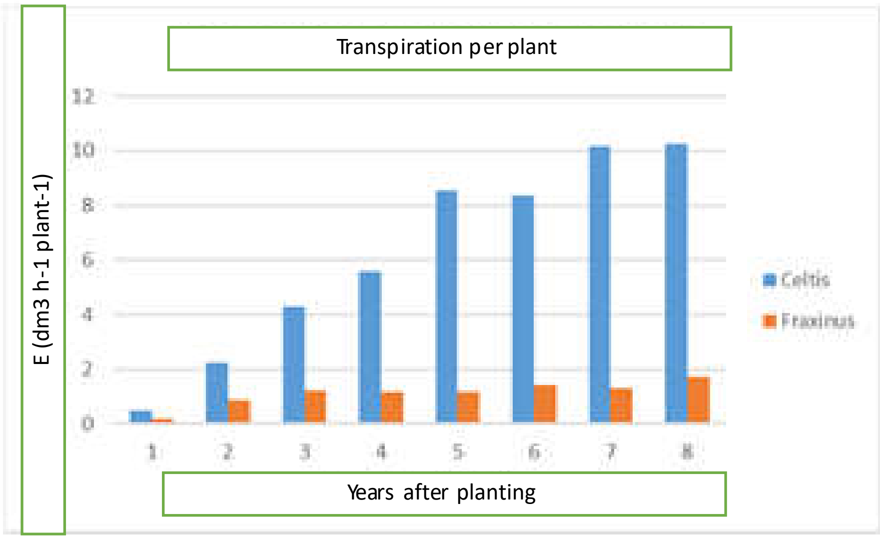
Transpiration per plant did



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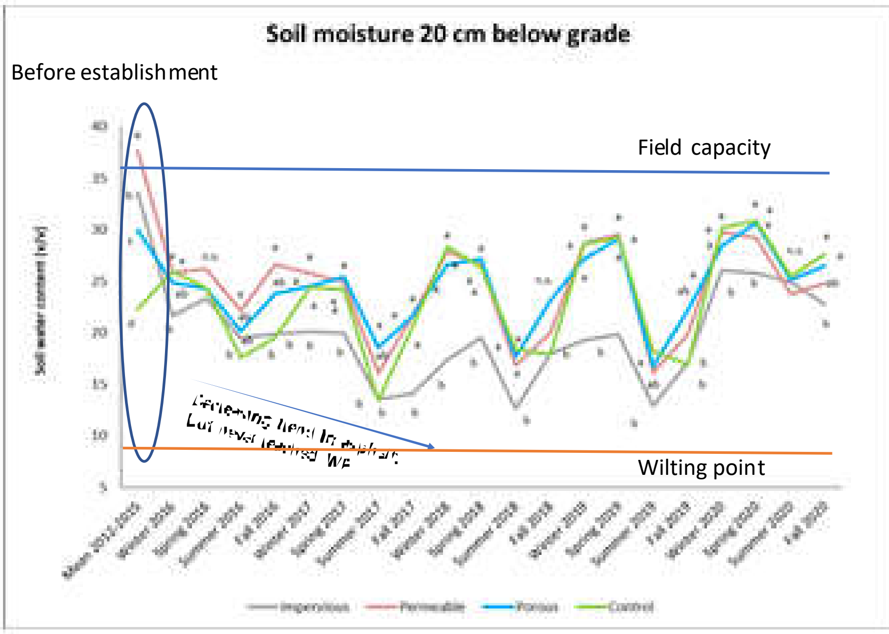
Soil moisture after establishment



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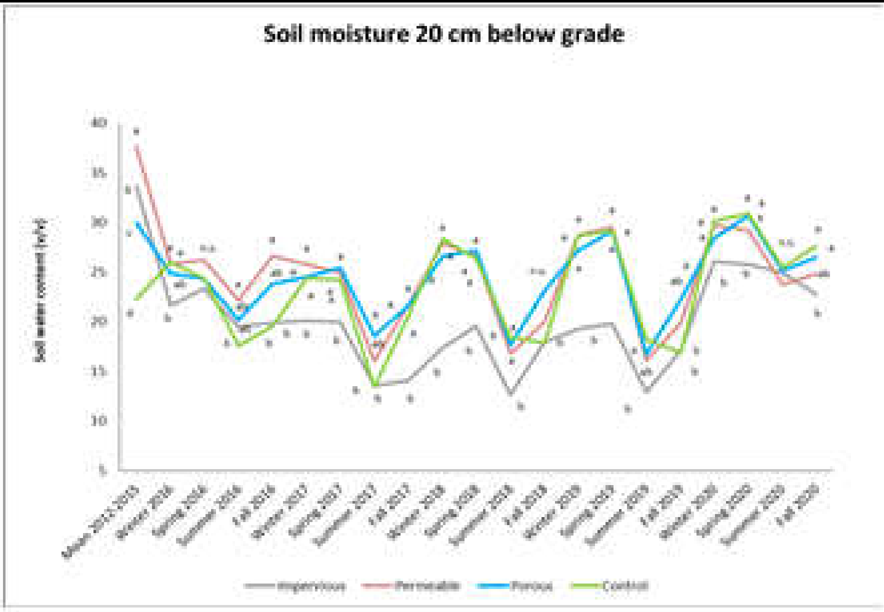

Major differences in winter and spring than in summer and fall identify a slower rehydration during the rainy period rather than a higher dehydration during summer

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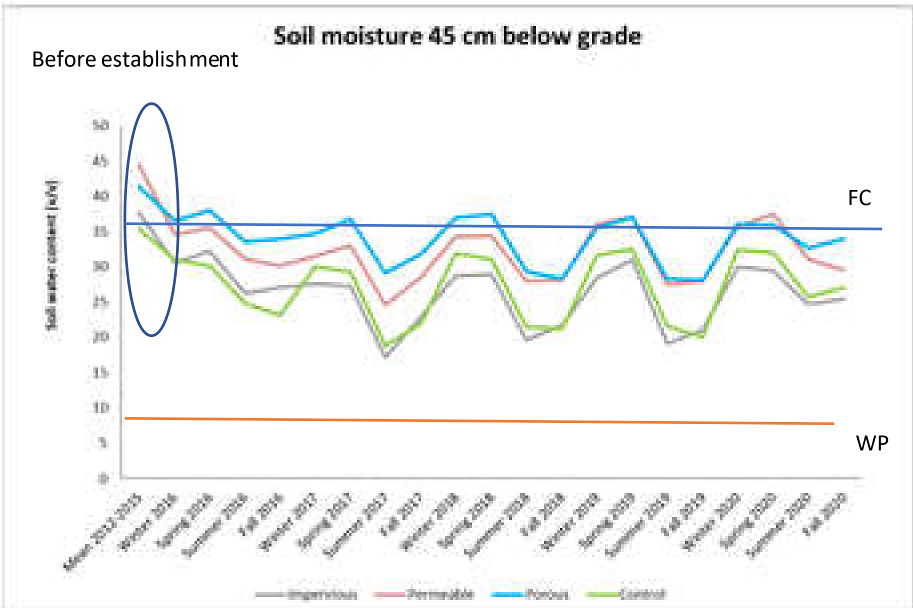
Soil moisture after establishment



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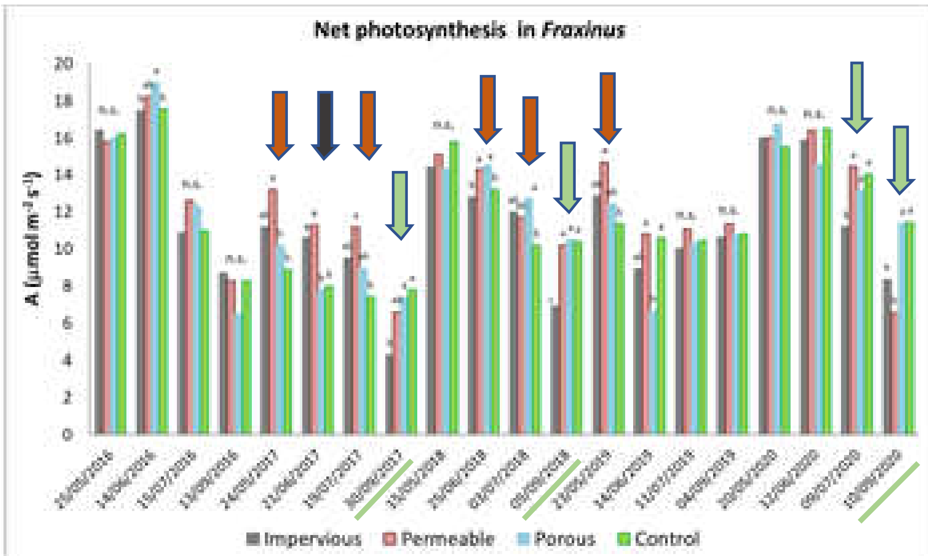
Did this change in soil moisture affect carbon gain?



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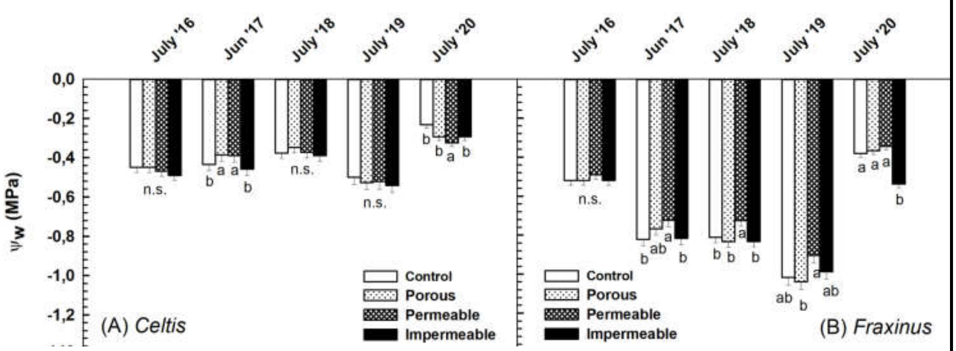
Did this change in soil moisture affect plant hydration?



Pre-dawn water potential is an indicator of plant hydration: the less it is negative, the more the plant is well-hydrated

In Celtis, there is no evidence that pavements consistently affected water potential
In Fraxinus, permeable pavements lead to less negative water potential in most years

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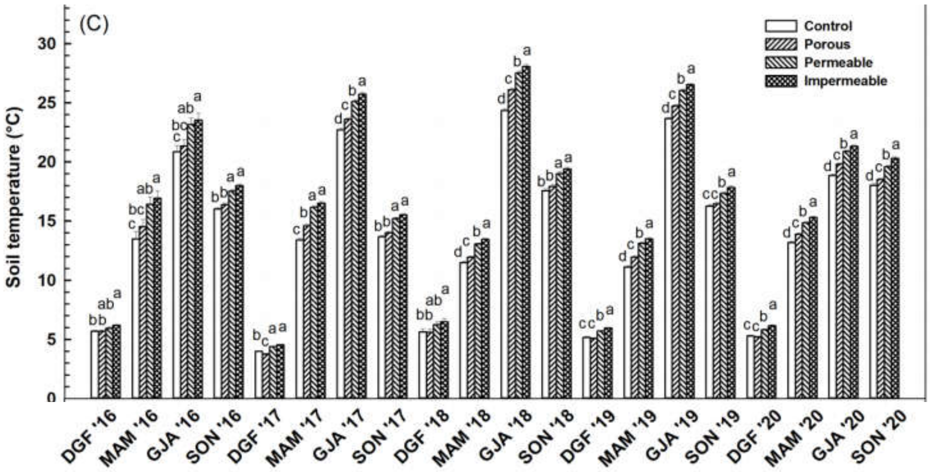
Temperature?



Soil beneath impermeable and permeable pavements was warmer than control

The maximum temperature reached was 28.1°C, far below the critical threshold for roots

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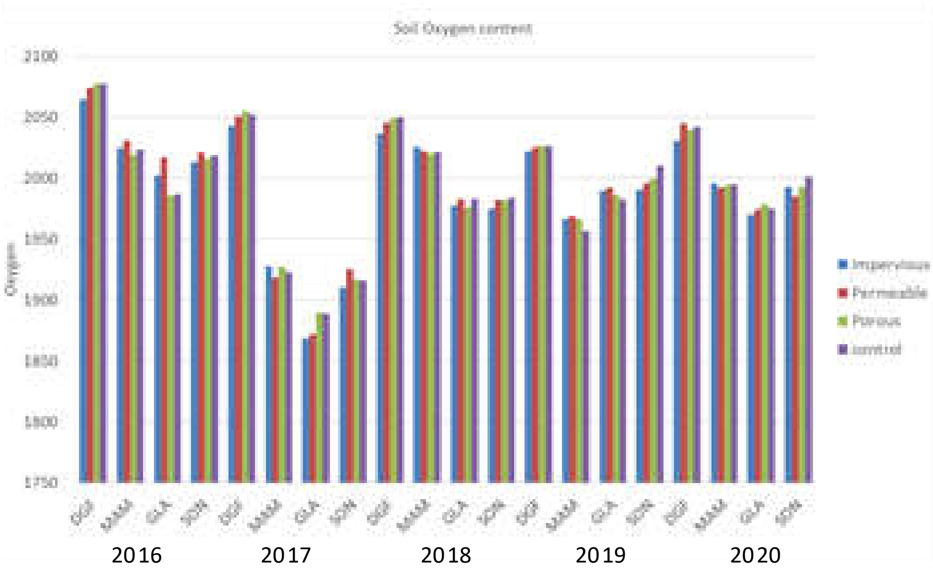
Oxygen availability?



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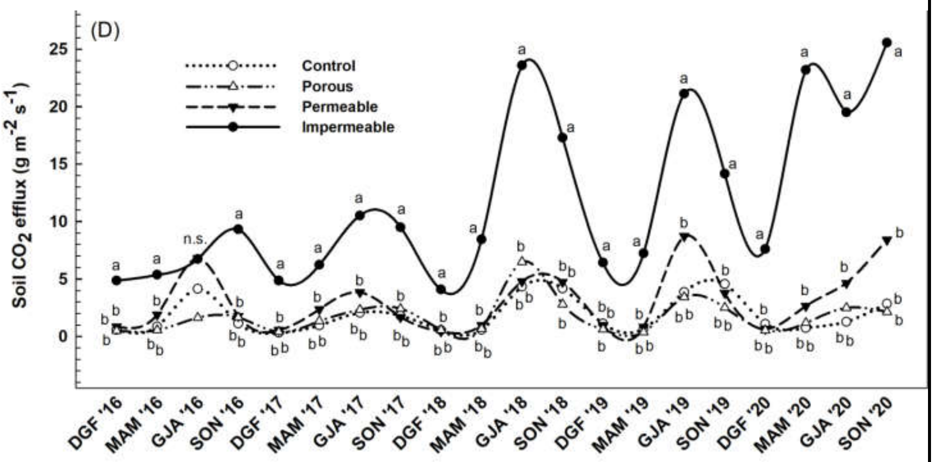
Elevated-soil-CO2?



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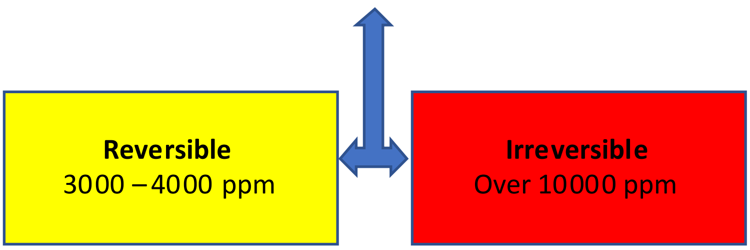
Recall:
Potential effects of soil CO_2 accumulation

- Inhibition of root respiration and root activity
- Reduction of root growth
- pH of root cells decreases



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Root studies

Root density, depth, and size

Size of the root system and root density for coarse roots, assessed in 2014 and 2020 on 24 plants (3 x treatment) using **Ground Penetrating Radar** (900 MHz antenna). Measurements in 2020 were conducted using TreeRadarUnit (TRU) in cooperation with Studio Planta (Turin, Italy)

scans every 20 cm

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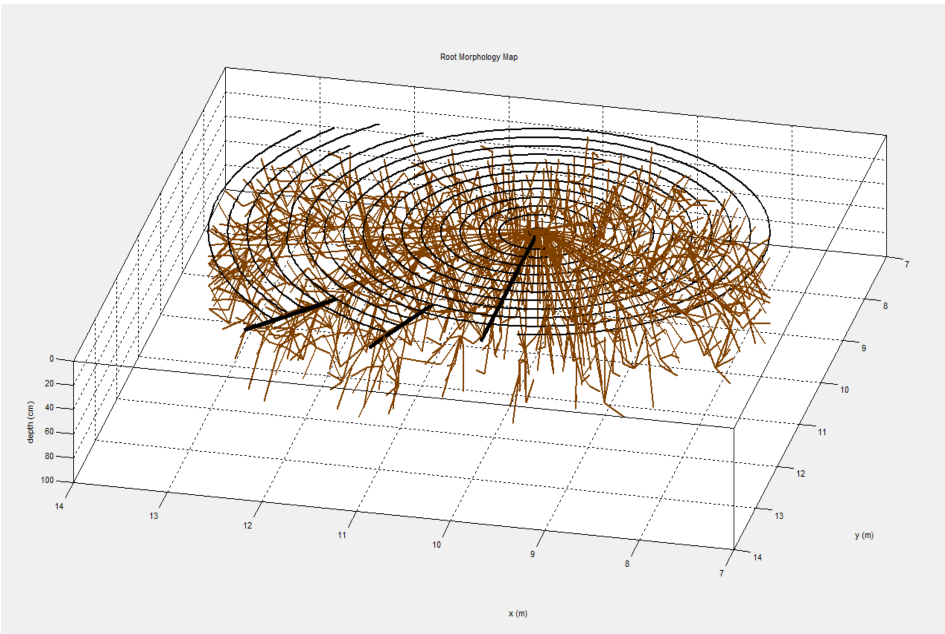

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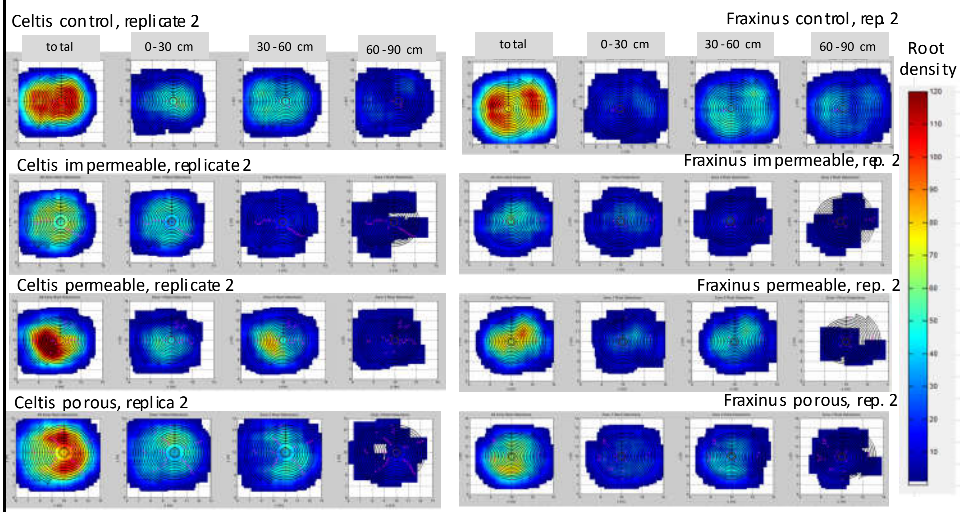
Growth – roots (GPR)



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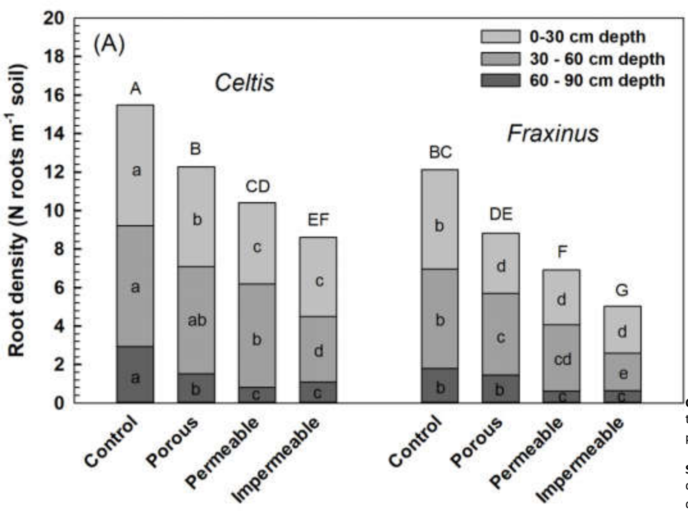

- Eighty-five to **92% of roots** were located in the **uppermost 60 cm** of soil;
- **Impermeable pavements increased** the fraction of **roots located in the uppermost 30 cm** below grade (47.7%) compared to other treatments (40.6%);
- **control trees had more deep roots** (> 60 cm below grade, 17.3%)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

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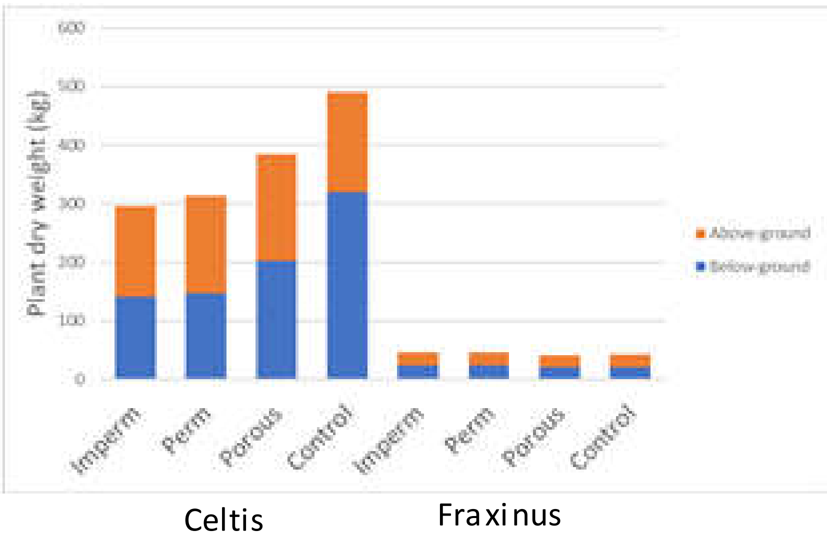
Removal of pavements

Done on 16-19 October 2020

Airspading and excavation of the whole root system

Plant dry biomass



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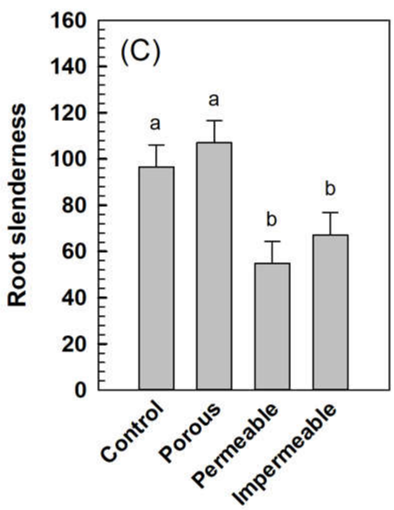

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Root biomass- fine vs. coarse roots

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

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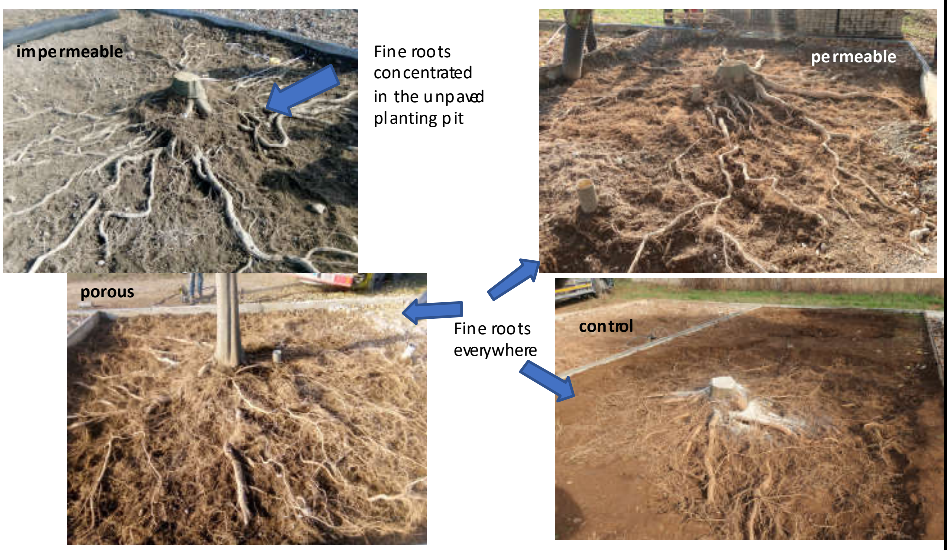

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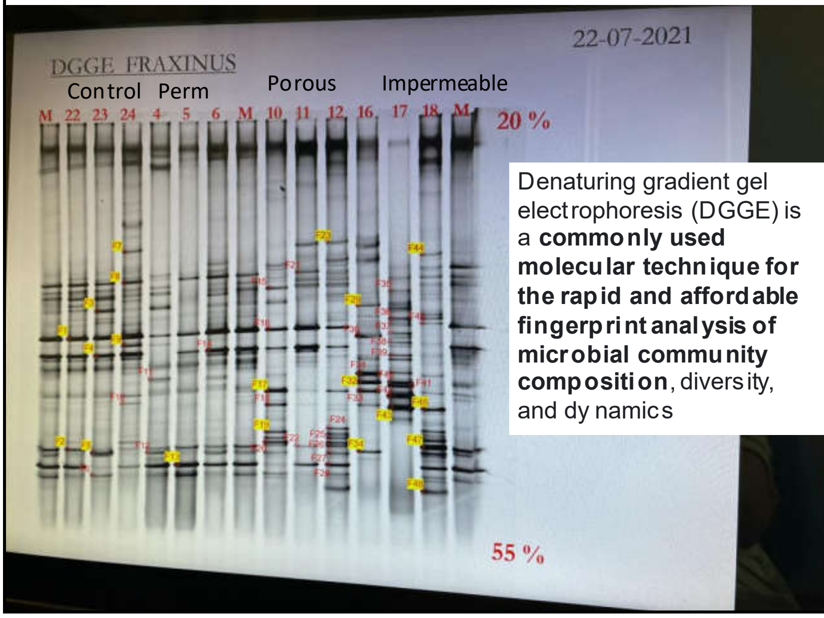
Root-associated microbiota
(in cooperation with University of Pisa)



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

Work in progress

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Stem DBH growth

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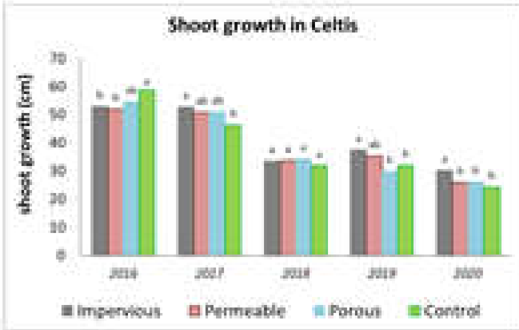
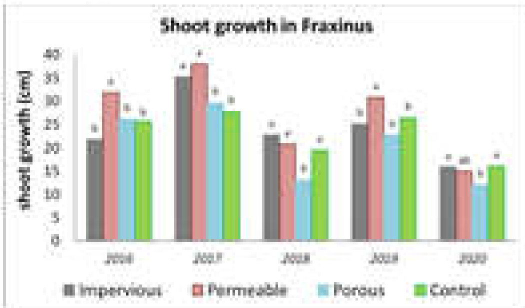
Shoot extension





Impermeable pavements did not reduce shoot extension

Shorter shoots were found in porous Fraxinus than in permeable Fraxinus

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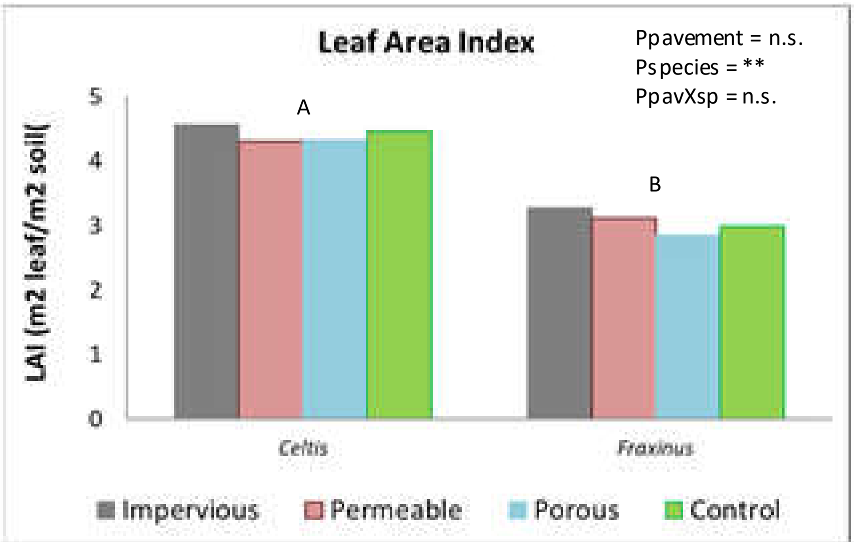
Leaf Area Index



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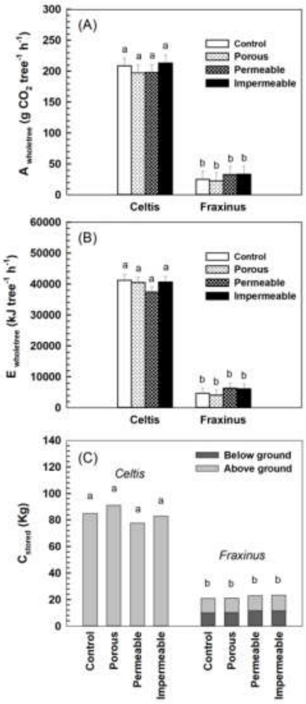
Ecosystem services..

- Awhole tree and Ewhole tree were calculated using a big leaf model.
- Pavements did not affect CO2 assimilation, carbon storage and latent heat dissipated by transpiration
- Celtis, 9 years after planting, provided far more ecosystem services than Fraxinus



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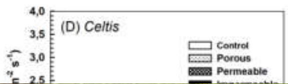
..and disservices



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- Even in established trees, pavements did not harm tree health nor caused stunted growth.
- The quality of soil beneath the pavement matters more than the pavement itself
- Species selection is crucial for ES delivery

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What about older trees?

LIFE URBANGREEN (2018-2021)

2 cities: Rimini (Italy) and Krakow (Poland)

10 woody species

2 city strata: paved and unpaved soil

LIFE URBANGREEN
(LIFE 17 CCA/ITA/000079)

LIFE URBANGREEN

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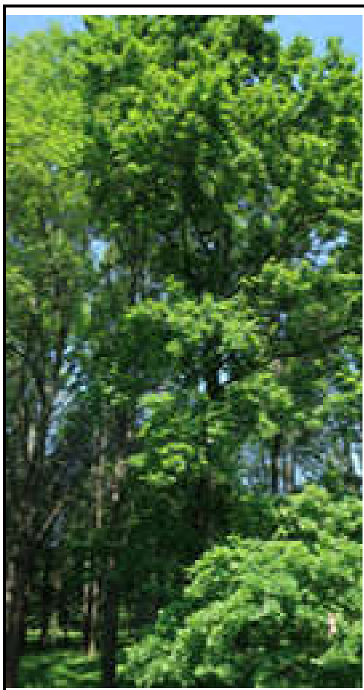

Street or park?

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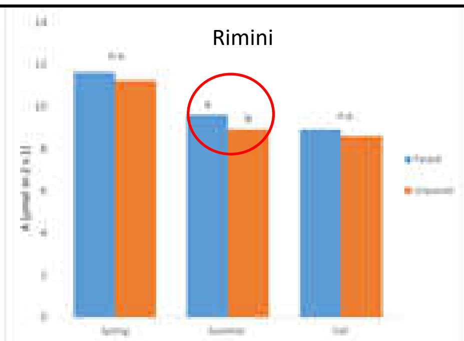
- In Rimini, **net CO2 assimilation was higher in street** than in park trees, particularly for *Aesculus, Acer, Q. ilex, and Q. robur* plants during summer



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Research wa funded by **TREE Fund Research Fellowship Grant Program** “Long-term assessment of the effects of impervious, permeable, and porous pavements on the underlying soil and on established trees”,

Finanziamento: 100’000 USD

Research Fellowship Grant Program

TREE FUND
Cultivating Innovation

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