LIFE URBANGREEN
(LIFE17 CCA/ITA/000079)

UNIVERSITÀ
DEGLI STUDI
DI MILANO

R3GIS
managing spaces

ProGea 4D

Anthea

Zarząd
Zieleni Miejskiej
w Krakowie

LIFE URBANGREEN

How trees improve cities: CO$_2$ uptake, cooling, and air quality amelioration

2022

Alessio Fini, Irene Vigevani, Denise Corsini, Alice Pasquinelli, Edoardo Cagnolati, Przemyslaw Szwalko Piotr Wezyk, Osvaldo Failla, Marco Gibin, Paolo Viskanic, Francesco Ferrini

ISA
MALMÖ 22

If I was a peach grower..

Prunus persica 'Bordò' = 250 q/ha

Prunus persica 'Big Top' = 350 q/ha

Prunus persica 'Stark Redgold' = 400 q/ha

Effect of training on yield

< 10-20%<

Quantification of urban trees ES provisioning

I-Tree

www.itreetools.org

Journal of Arboriculture 29(1): January 2003 1

A BENEFIT–COST ANALYSIS OF TEN STREET TREE SPECIES IN MODESTO, CALIFORNIA, U.S.

by E. Gregory McPherson

Greening

www.elsevier.com/locate/ufug

removal by urban forests in Canada and its effect on air quality human health

David J. Nowak[a,*], Satoshi Hirabayashi[b], Marlene Doyle[c], Mark McGovern[c], Jon Pasher[c]

SmartUrban

www.resolvo.eu/case-studies/smarturban

Build. Simul.

https://doi.org/10.1007/s12273-018-0490-4

Modelling the effect of … and air quality: The SMA…

…dani[a,*], Marco Napoli[a], Francesco Ferrini[a], Alessio Fini[a,b], … Alberto Giuntoli[a]

No method currently exists that can directly evaluate ES by urban greenery. All approaches used rely on indirect estimates and are prone to uncertainties (Velasco et al., 2016).

Envi-met

https://www.envi-met.com/it/

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Original article

Preliminary study of the influence of the spatial arrangement of urban parks on local temperature reduction

Bau-Show Lin*, Ciao-Ting Lin

Department of Horticulture and Landscape Architecture, National Taiwan University, NO.138, Sec. 4, Keelung Rd., Taipei, 10617, Taiwan, ROC

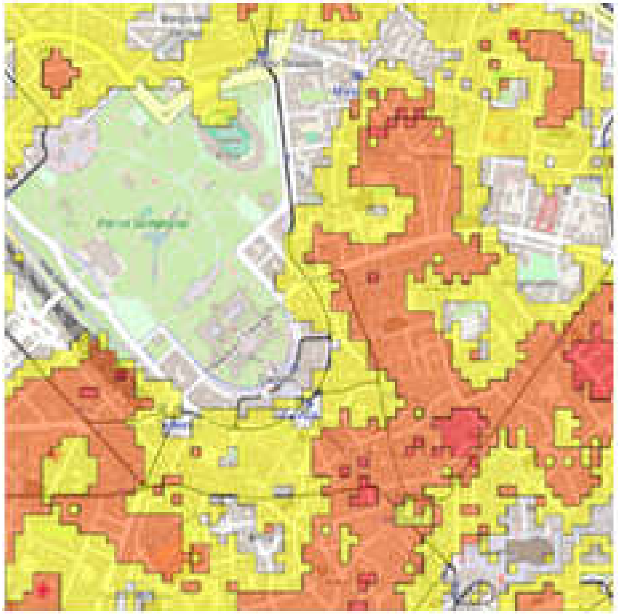
Quantification of urban trees ES provisioning

Micro-climatic models

$$F = V_d \times C$$

PMx

$$v_d = \frac{1}{r_a + r_b + r_c}$$



Cooling

Mariani et al., 2016, STOTEN

Growth curves

CO$_2$ storage and sequestration

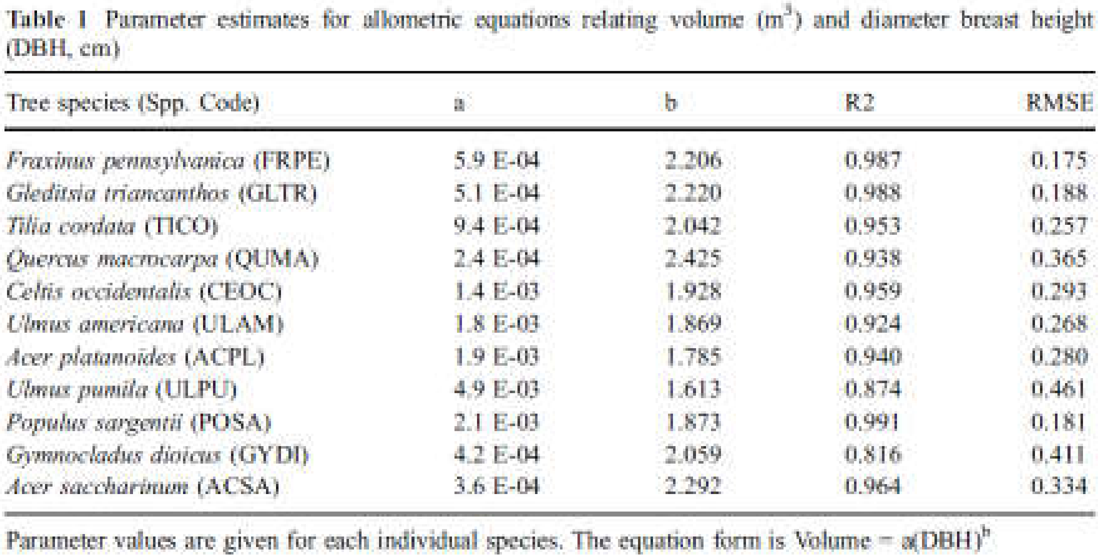
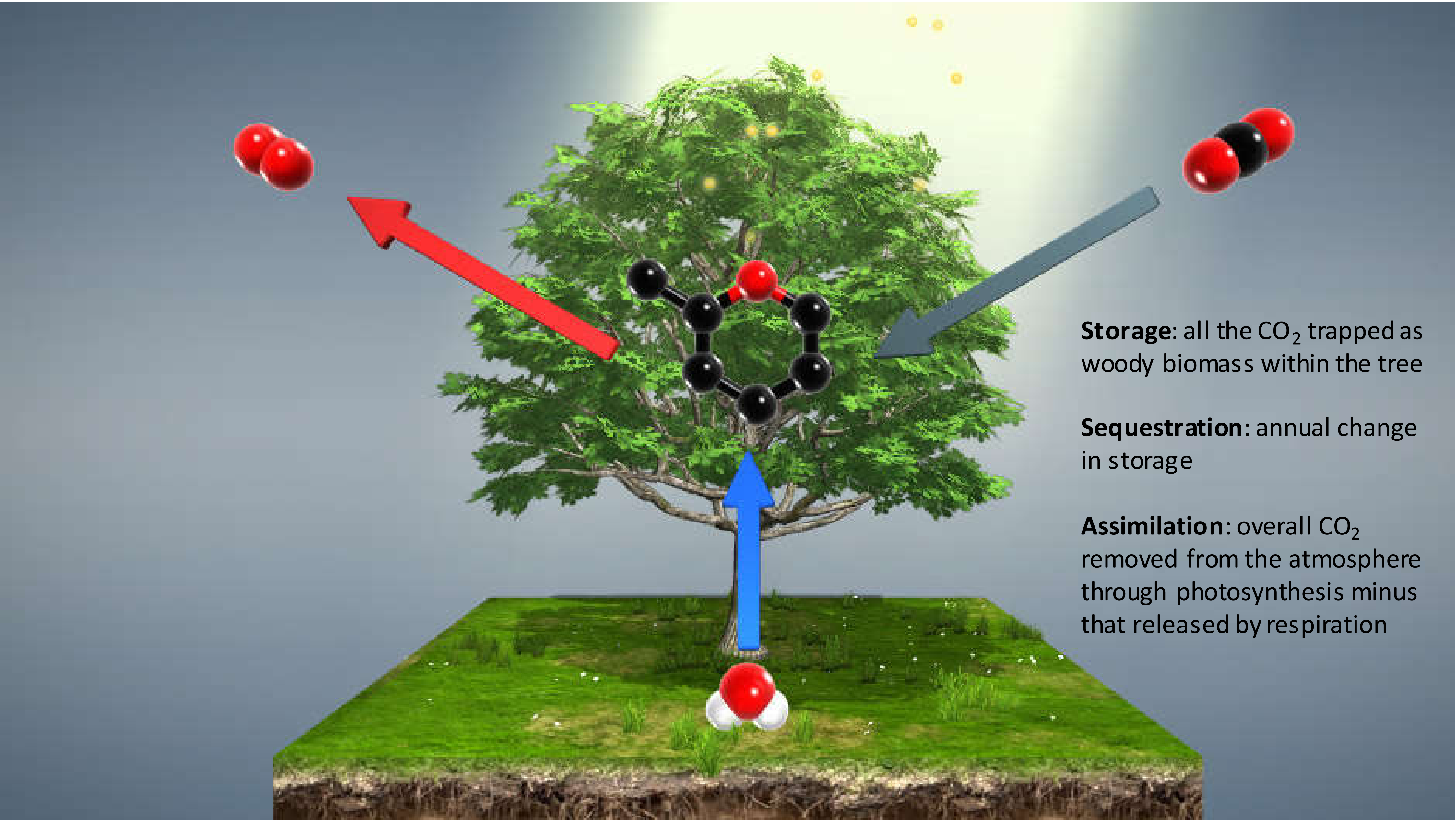


Table 1 Parameter estimates for allometric equations relating volume (m^3) and diameter breast height (DBH, cm)

Tree species (Spp. Code)	a	b	R2	RMSE
Fraxinus pennsylvanica (FRPE)	5.9 E-04	2.206	0.987	0.175
Gleditsia triancanthos (GLTR)	5.1 E-04	2.220	0.988	0.188
Tilia cordata (TICO)	9.4 E-04	2.042	0.953	0.257
Quercus macrocarpa (QUMA)	2.4 E-04	2.425	0.938	0.365
Celtis occidentalis (CEOC)	1.4 E-03	1.928	0.959	0.293
Ulmus americana (ULAM)	1.8 E-03	1.869	0.924	0.268
Acer platanoides (ACPL)	1.9 E-03	1.785	0.940	0.280
Ulmus pumila (ULPU)	4.9 E-03	1.613	0.874	0.461
Populus sargentii (POSA)	2.1 E-03	1.873	0.991	0.181
Gymnocladus dioicus (GYDI)	4.2 E-04	2.059	0.816	0.411
Acer saccharinum (ACSA)	3.6 E-04	2.292	0.964	0.334

Parameter values are given for each individual species. The equation form is Volume = a(DBH)^b

McHale et al., 2009, Urban Ecosys



Storage: all the CO_2 trapped as woody biomass within the tree

Sequestration: annual change in storage

Assimilation: overall CO_2 removed from the atmosphere through photosynthesis minus that released by respiration

LIFE URBANGREEN (2018–2022)

2 cities: Rimini (IT) and Krakow (PL)

10 model woody species in each city

Aims:

1- Use eco-physiological traits for ES estimates

2- use tree eco-physiol[illegible]gy to set management st[illegible]gies

3- evalu[illegible]e effect of sound m[illegible]gement on ES

Work in progress

Experimental sites

Parameter (30-y-average)	Rimini	Krakow
Climate zone (Koppen)	Cfa	Cfb
Tmin (°C)	8,6	3,8
Tmax (°C)	17,6	12,8
Rainfall (mm)	705	622
Size of experimental area (ha)	250	470
Planting density (plants/ha)	179	244

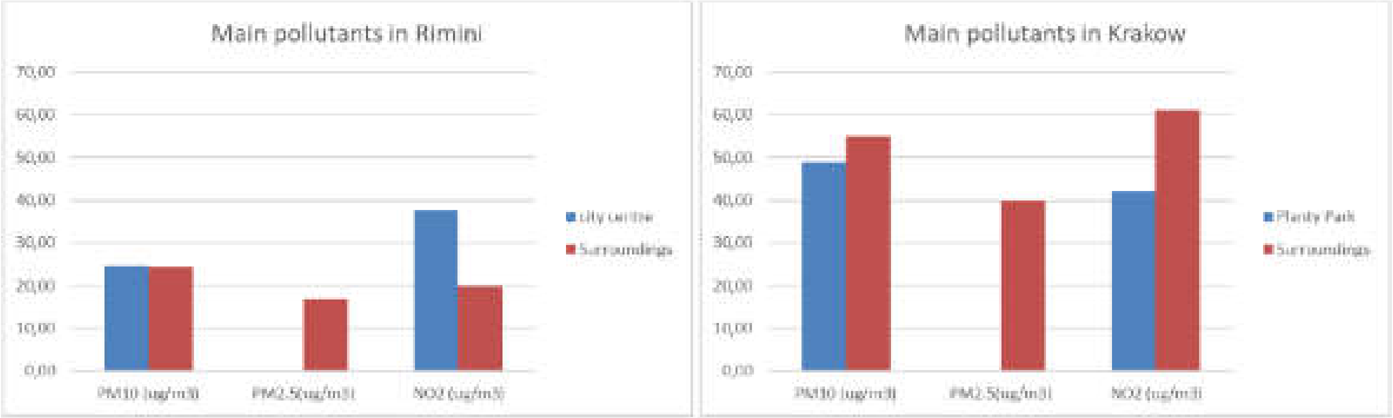


Fig. 1 - Average PM10, PM2,5, and NO2 in the two cities.[1]

Stratification

Experimental areas were stratified in:

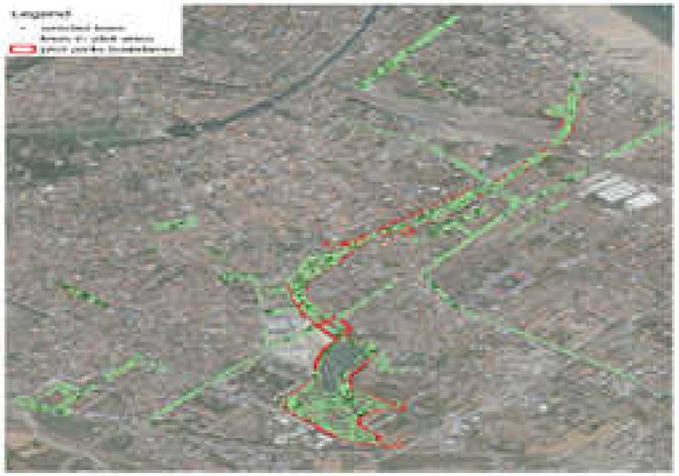
Paved areas: street trees, trees in parking lots, tree planted in well-defined planting pits or with visible conflicts with the built environment

Unpaved areas: tree in parks and gardens, growing in unpaved soil with negligible conflicts with the built environment

Trees in the experimental areas

Krakow, PL

Rimini, IT



- Ten model species per city were selected
- The selected genera accounted for 65% and 57% of total tree population in Rimini and Krakow, respectively

Species	n.	DBH min. (cm)	DBH max. (cm)
Rimini			
Acer negundo L.	80	7.50	67.62
Aesculus hippocastanum L.	105	5.00	76.43
Ligustrum lucidum Aiton	76	8.00	30.90
Platanus x acerifolia (Aiton) Willd.	78	5.30	77.55
Populus nigra L. 'Italica'	78	7.50	92.36
Prunus laurocerasus L.	12	4.00	37.88
Quercus ilex L.	110	11.50	109.18
Quercus robur L. 'Pyramidalis'	89	8.00	51.43
Tilia x europaea L.	109	6.20	58.93
Krakow			
Acer platanoides L.	135	5.00	84.39
Aesculus hippocastanum L.	125	4.50	109.71
Cornus alba L.	29	2.23	8.46
Fraxinus excelsior L.	128	4.50	84.87
Populus nigra L. 'Italica'	96	7.00	96.80
Quercus robur L.	126	5.00	129.14
Sorbus aucuparia L.	103	4.00	50.64
Tilia cordata Mill.	146	5.00	74.73
Ulmus laevis Pall.	87	4.00	118.15

Tree age, DBH, and crown radius

Tree age was retrieved with the assistance of Anthea and ZZM (municipal tree care companies)

About 800 combined measurements of **stem DBH, crown radius** and **crown projection area** (CPA) were done per city (Pretsch et al., 2015)

For multi-stemmed trees, diameter was measured at 30 cm height following the I-Tree protocol.

Data were used to generate allometric curves that correlate tree age with DBH and DBH with CPA

$$\mathbf{DBH = b * age^{a}}$$

$$\mathbf{CPA = \pi * R_{canopy}^{2} = \pi * (b * DBH^{a})^{2}}$$

Species	**b**	**a**	**R2**	**Function**
Acer negundo	1,11393344815083	0,92401978988030	0,883	$DBH = b * age^{a}$
Aesculus hippocastanum	0,95897047949680	0,99963633912339	0,947	$DBH = b * age^{a}$
Quercus robur	2,10141368488829	0,75820986641471	0,736	$DBH = b * age^{a}$
Prunus laurocerasus	2,25460849836377	0,61414876018813	0,468	$DBH = b * age^{a}$
Quercus ilex	2,90733535606017	0,66277907159766	0,781	$DBH = b * age^{a}$
Ligustrum lucidum	3,56302969814312	0,45074695375881	0,416	$DBH = b * age^{a}$
Populus nigra	1,28491363078834	1,00839853426417	0,897	$DBH = b * age^{a}$
Platanus x acerifolia	0,65017485710193	1,14619326101069	0,858	$DBH = b * age^{a}$
Tilia x europaea	1,50390917211331	0,90314882990627	0,887	$DBH = b * age^{a}$
Pinus pinea	N.A.	N.A.	N.A.	N.A.

Leaf gas exchange per unit leaf area

An infra-red gas analyser was used to screen plants for net CO_2 assimilation (Asat) and transpiration (Esat) per unit leaf area.

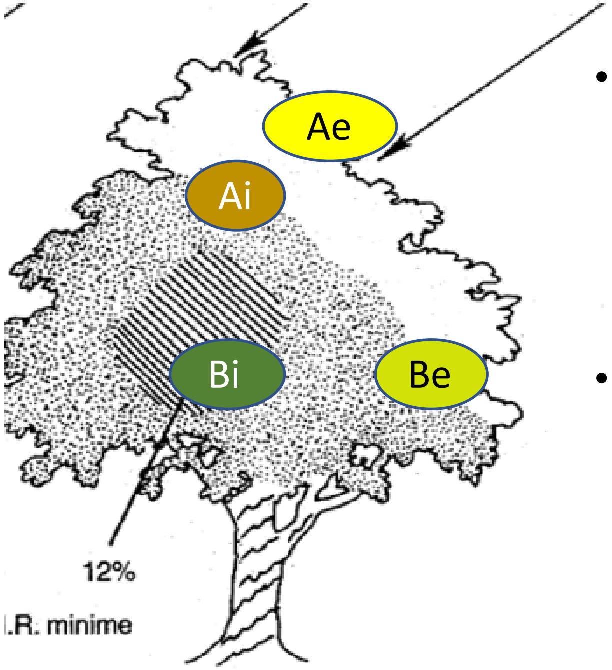
Three leaves per plant (from apical, medial, and basal canopy layers) were placed in a cuvette, under set external CO_2 concentration (=420 ppm), temperature (=ambient) and irradiance (=saturating)

Measurements were conducted from summer 2018 to fall 2019 on 14 (Krakow) and 11 (Rimini) replicate plants per species and strata, selected as representative of each species DBH-distribution.

Asat and Esat were measured on a total of 4356 (Krakow) and 3564 (Rimini) leaves over the experiment

Refining the leaf gas exchange measurements

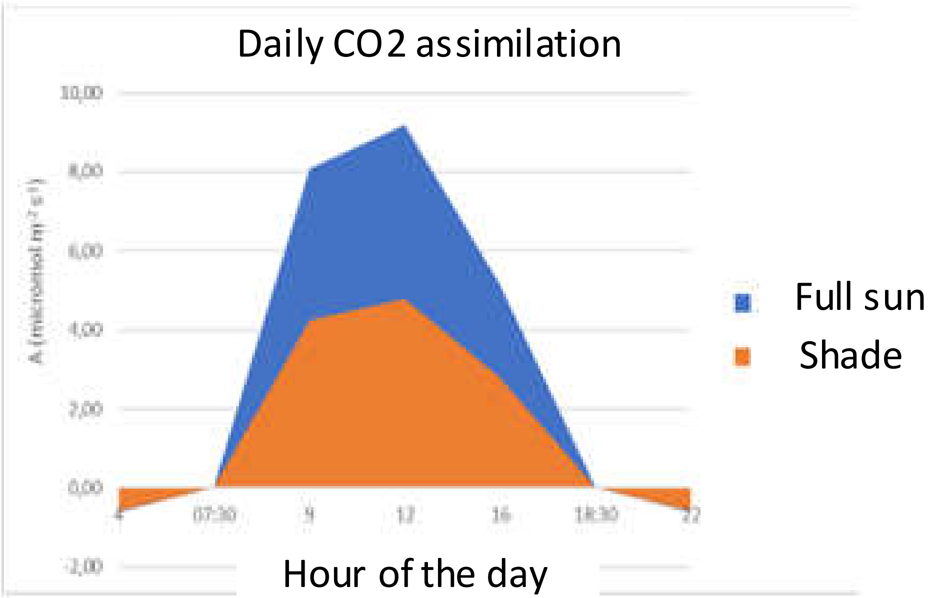
Full sun and shaded leaves coexist within a canopy



- The canopy of each plant was divided in 2 layers (apical (a) and basal (b) canopy layers).
- Each layer consisted in sun, external (e) and shaded, internal leaves (i)

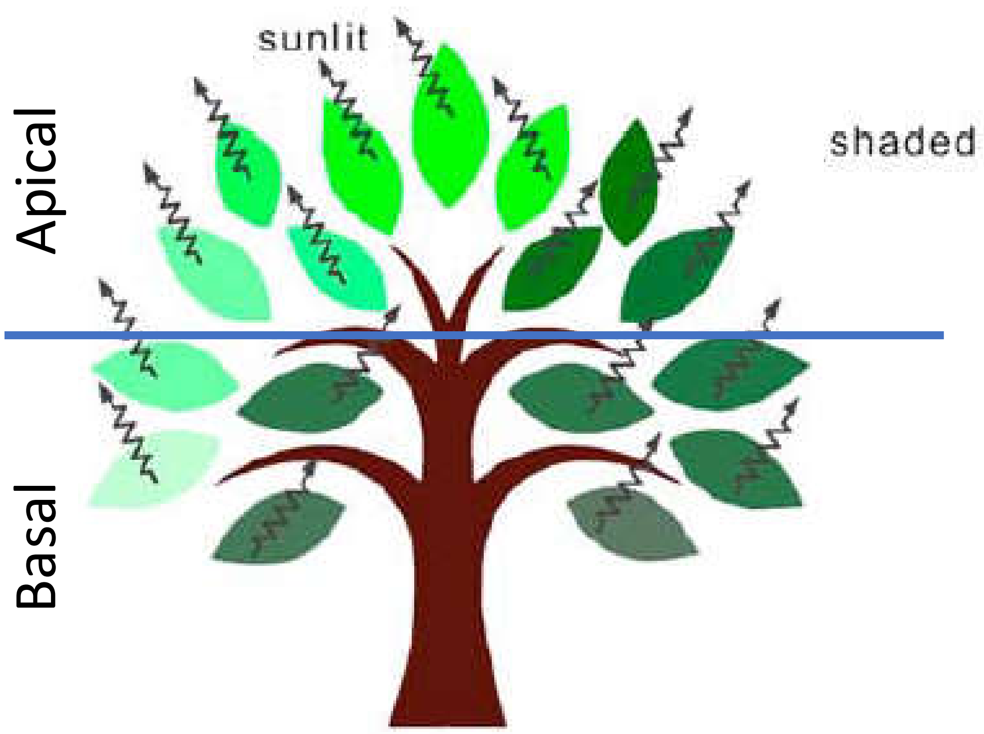
Six replicate plants per species and strata were selected for daily leaf gas exchange measurements
About 6900 leaves were measured in each city over the experiment

Photosynthesis is not constant through the day



Daily measurements on each leaf class were conducted at 4 time-points per day on the same individuals: morning, midday, afternoon and night, at growing irradiance

Upscaling from leaf to canopy



Multi-layer – definition and calculations

- The canopy is divided in layers: we used two layers (apical and basal)
- Each layer is divided into full sun and shaded leaves
- **AtreeML = CPA * (Adaily$_{sun}$ * LAI$_{sun}$ + Adaily$_{shade}$ * LAI$_{shade}$)**
- Equations to calculate sun and shaded leaf area:
- **LAI_{sun} = = $2\cos\theta * (1 - e^{-0.5*\Omega*LAI/\cos\theta})$** and
- **$LAI_{shade} = LAI - LAI_{sun}$**

where θ is solar zenith angle (rad)

AtreeML = CO2 assimilation per day per tree
CPA = crown projection area
Adaily = CO2 assimilation per day per unit leaf area
LAI = leaf aea index

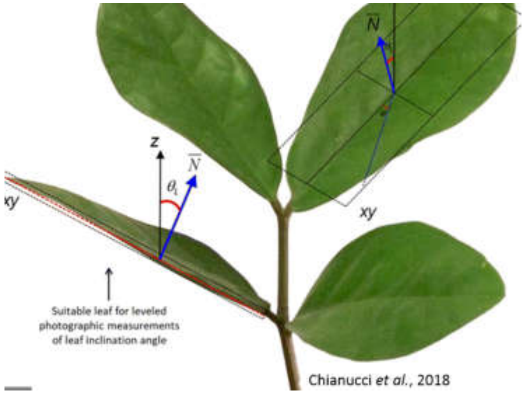
Plant, Woody, and Leaf Area Index

The apparent effective Plant area index (i.e. half of total leaf + woody area per unit horizontal soil area) was measured using the ceptometer Accupar on 6 (Rimini) or 7 (Krakow) replicate plants per species and strata.

Measurements were conducted in May, June, and July between 11.30 and 14.30

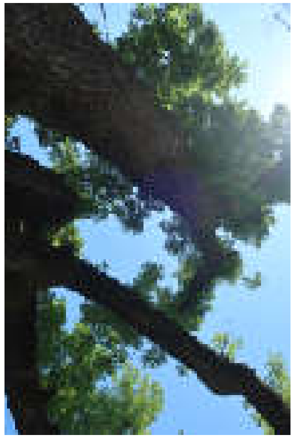
Measured PAIe

Leaf angle distribution

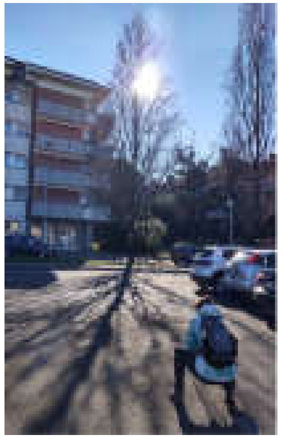


Chianucci *et al.*, 2018

Clumping



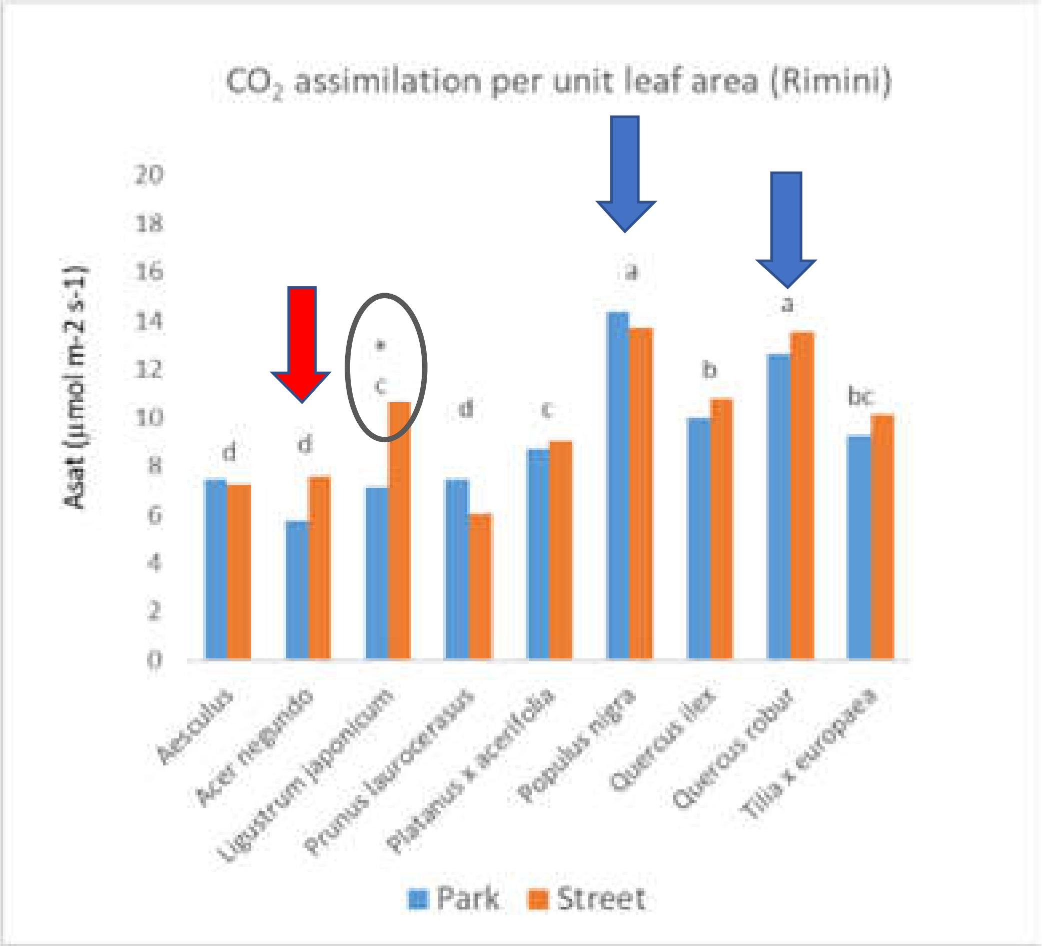
Woody area/Plant area

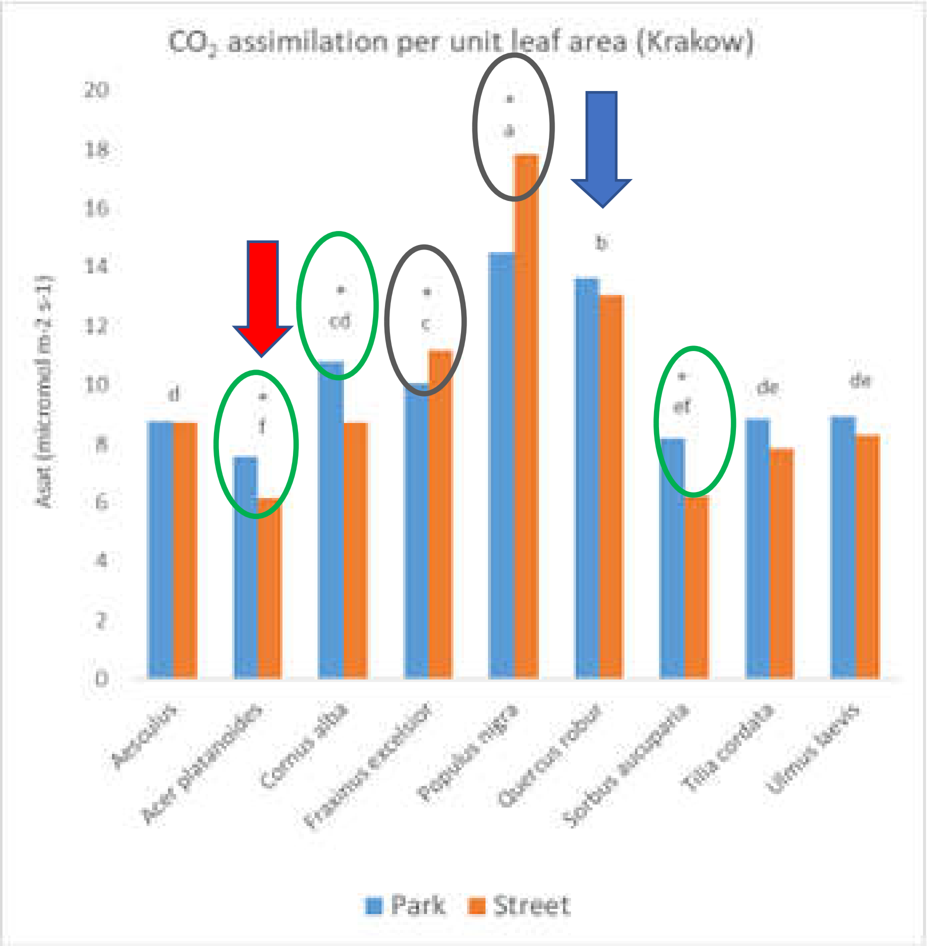


True LAI

For details, see Yan et al., 2019, Agricultural and Forest Meteorology 265: 390–411

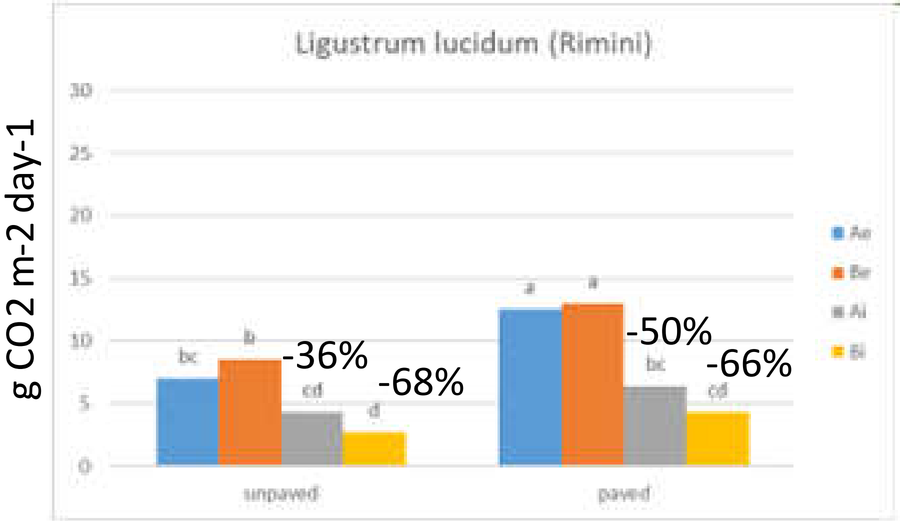
Net CO$_2$ assimilation per unit leaf area at saturating irradiance



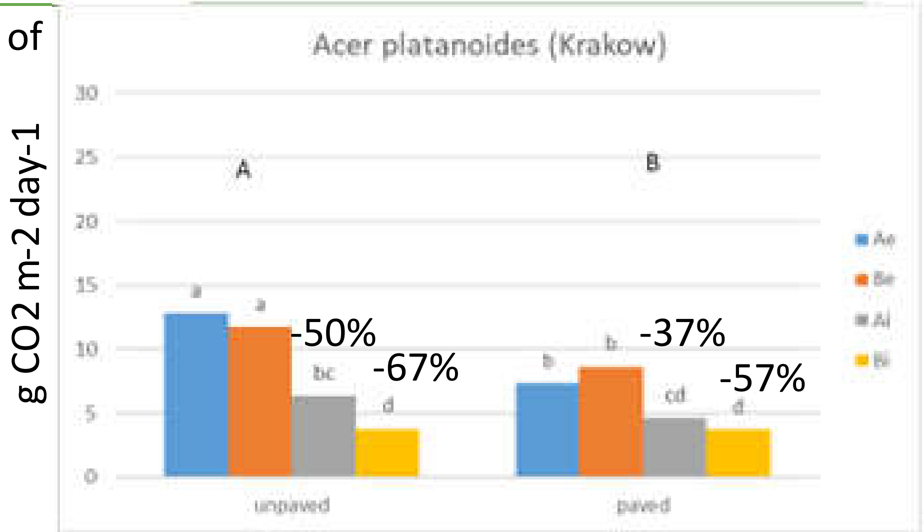


Different letters denote significant differences among species at $P<0.01$.
* denotes significant differences between strata at $P<0.01$.

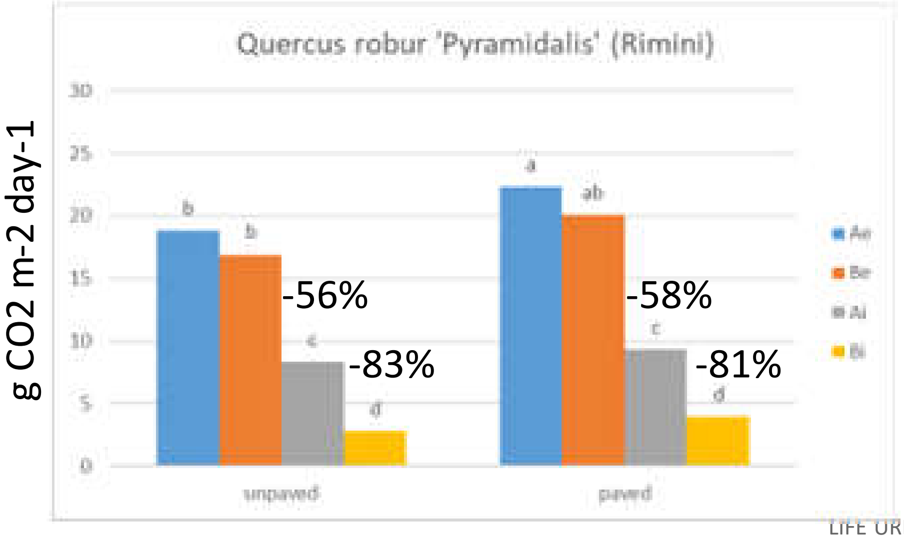
Daily CO_2 assimilation per unit leaf area of full sun and shaded leaves


Ligustrum lucidum (Rimini)

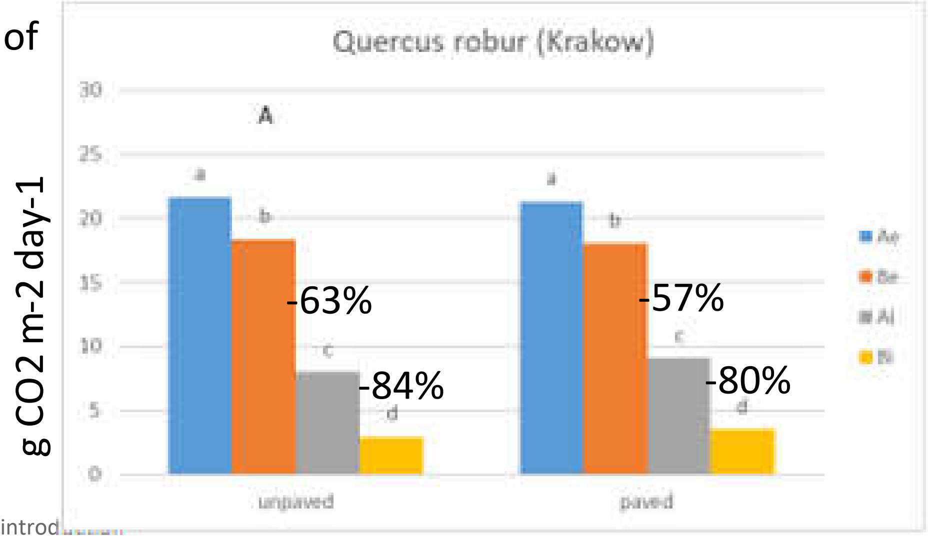
High contribution of shaded leaves


Acer platanoides (Krakow)

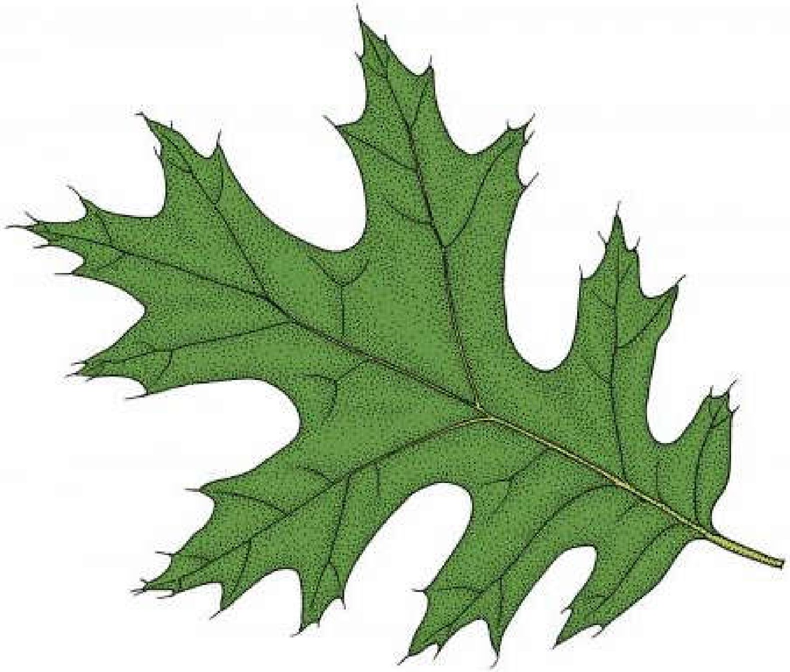
Canopy layers:
Ae = apical, full sun
Ai = apical, shaded
Be = basal, full sun
Bi = basal, shaded


Quercus robur 'Pyramidalis' (Rimini)

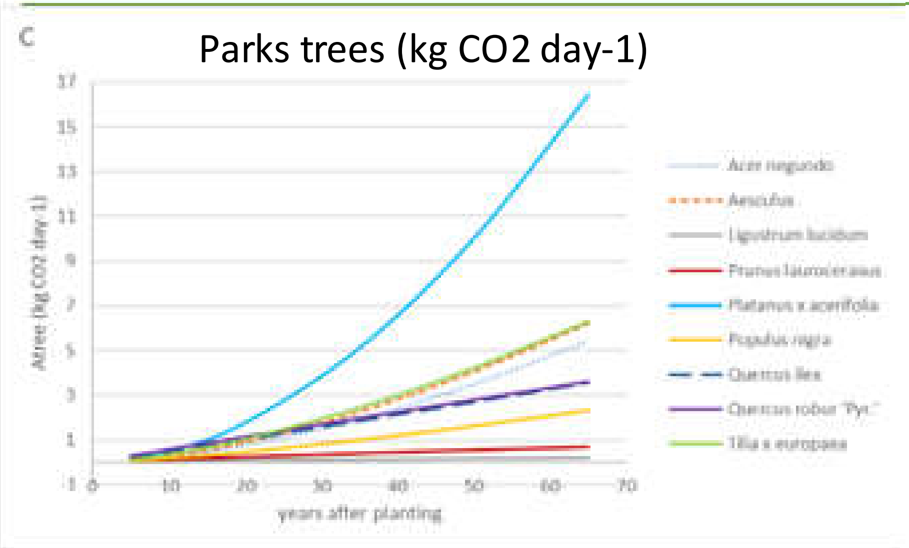
Low contribution of shaded leaves


Quercus robur (Krakow)

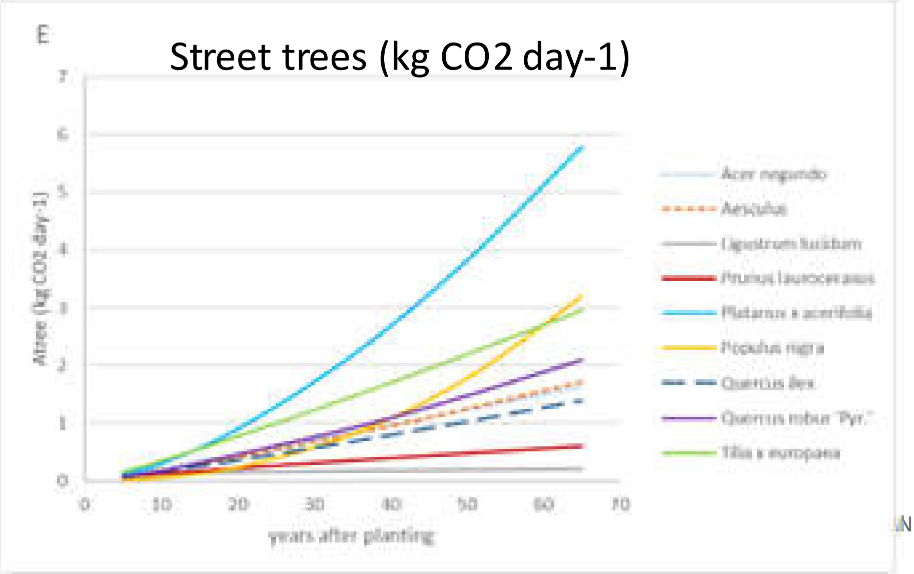
From leaf to canopy



Daily CO_2 assimilation per tree over a 65-yr life-cycle (Rimini)



Parks trees (kg CO2 day-1)

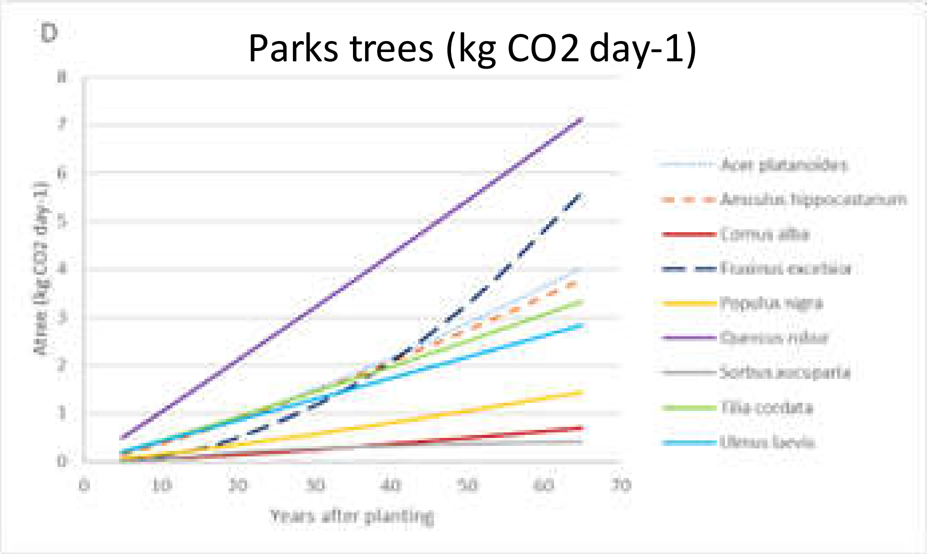


Street trees (kg CO2 day-1)

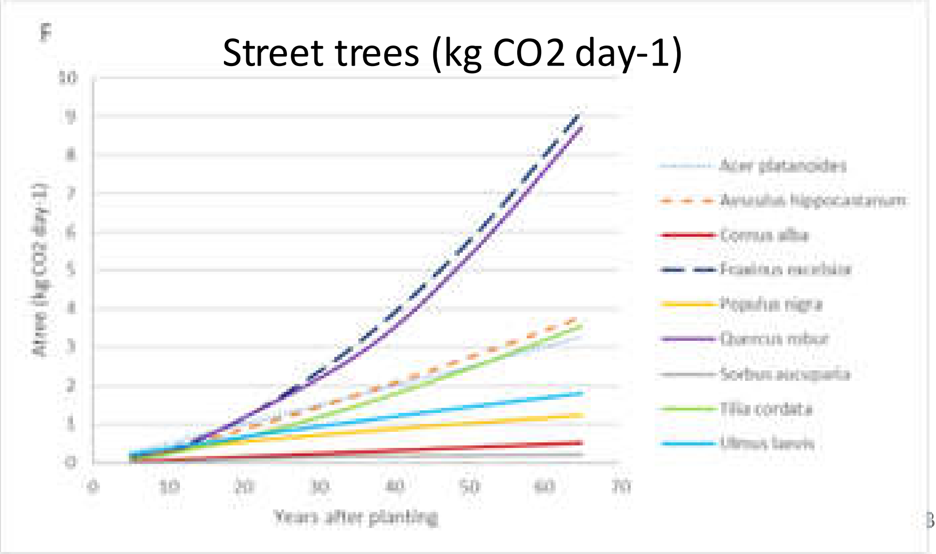
Park trees:
Q. Robur 'Pyramidalis' had higher Atree (about 0.594 kg CO_2 day^{-1}) for 12 years after planting.
Then, *P. x acerifolia* outcompeted other species (16.4 kg CO_2 day^{-1})

Street trees:
Tilia x europaea had higher Atree (about 0.368 kg CO_2 day^{-1}) for about 15 years after planting.
Then, *P. x acerifolia* displayed higher Atree (5.80 kg CO_2 day^{-1})

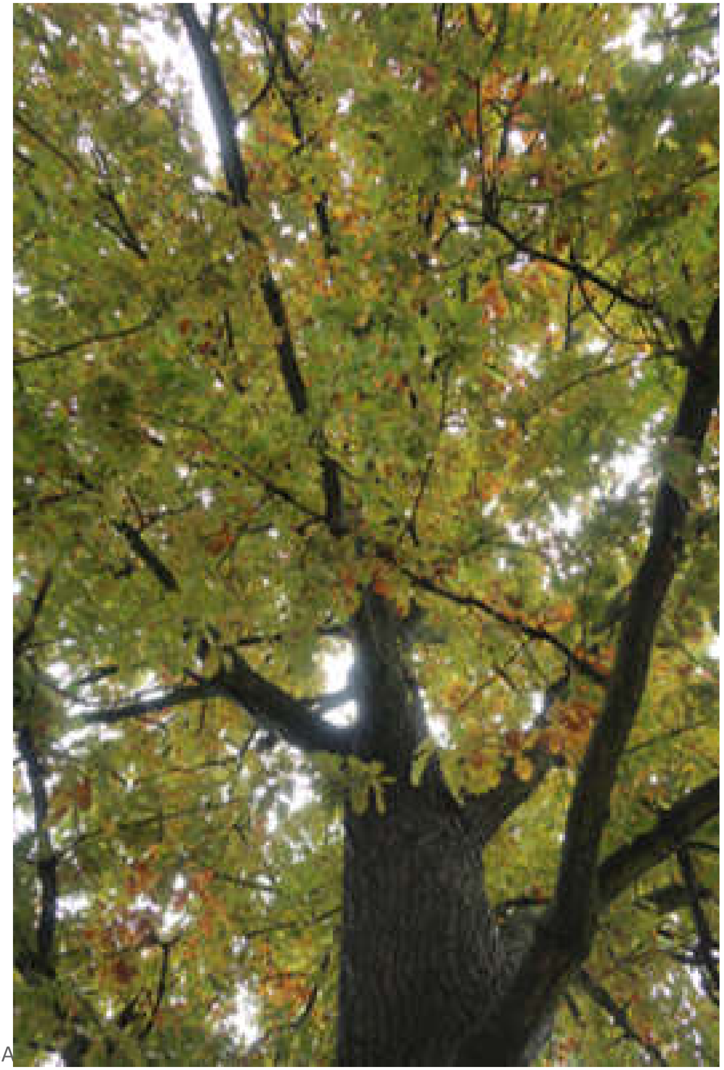
Daily CO_2 assimilation per tree over a 65-yr life-cycle (Krakow)



Parks trees (kg CO2 day-1)



Street trees (kg CO2 day-1)



Q. robur and *F. excelsior* provided higher A_{tree} in both parks and streets (up to 8 kg CO_2 day^{-1} 65 years after planting)

In parks, to get the best from ash, life-span should be enhanced

A. platanoides is suitable for short-term street tree plantings because it is the species which had higher A_{tree} in the early post-establishment period (about 0.150 kg CO_2 day^{-1} for a Norway maple 10 years after planting)

CO$_2$ storage and sequestration

A terrestrial laser scanner RIEGL VZ 400i was used by project partner Progea 4D to collect point clouds of 120 trees, during the leaf-off period.

Point clouds were converted into volumes of trunk and main branches using specific algorithms

troduction

CO_2 storage and sequestration

Volume of trunk and main branches was fitted against DBH using a sigmoid function:

$$V_{abg} = e^{b+a/DBH}$$

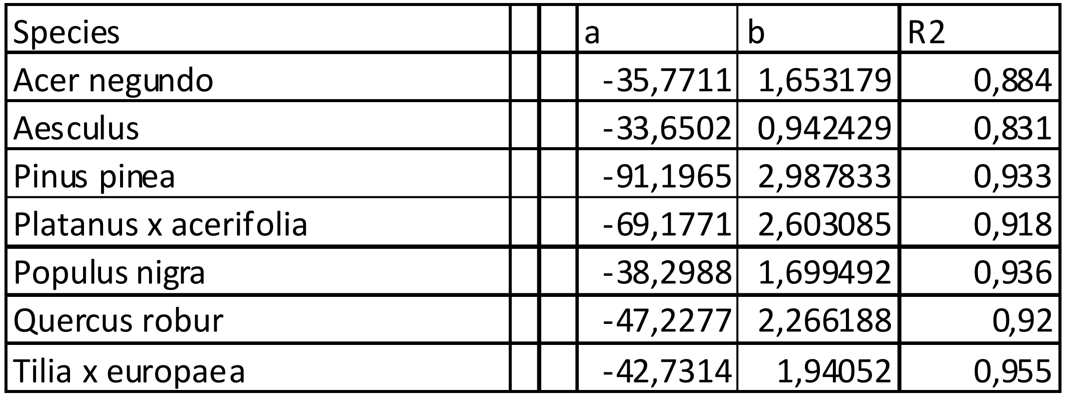
CO_2 storage was calculated as:

$$CO_2\text{stored} = 3{,}66 * 0{,}5 * 1{,}28 * V_{abg} * \text{Dry Dens.}$$

CO_2 sequestration was calculated as:

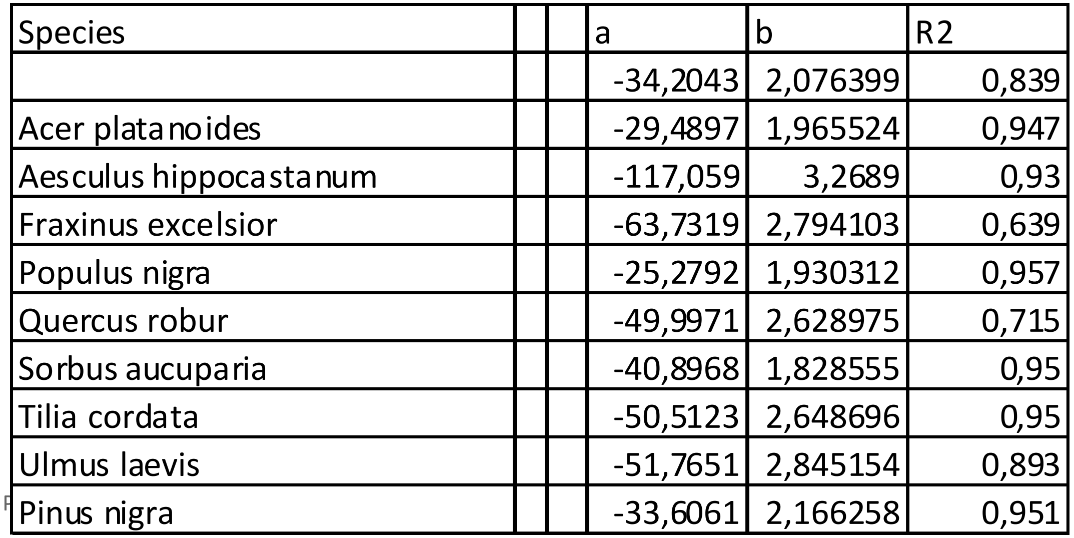
$$CO_2\text{seq} = CO_2\text{stored}_{t1} - CO_2\text{stored}_{t0}$$

Rimini



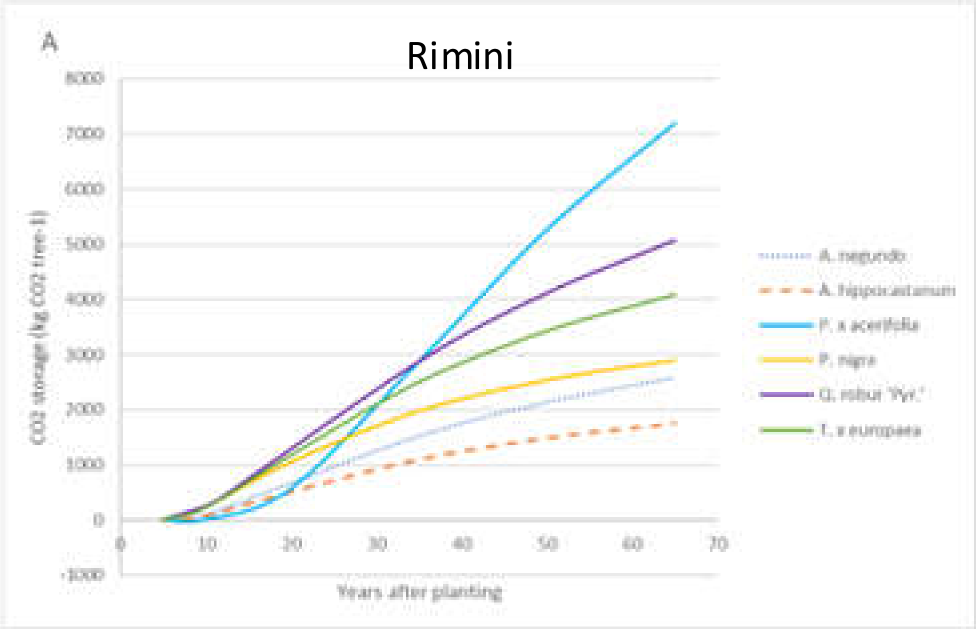
Species			a	b	R2
Acer negundo			-35,7711	1,653179	0,884
Aesculus			-33,6502	0,942429	0,831
Pinus pinea			-91,1965	2,987833	0,933
Platanus x acerifolia			-69,1771	2,603085	0,918
Populus nigra			-38,2988	1,699492	0,936
Quercus robur			-47,2277	2,266188	0,92
Tilia x europaea			-42,7314	1,94052	0,955

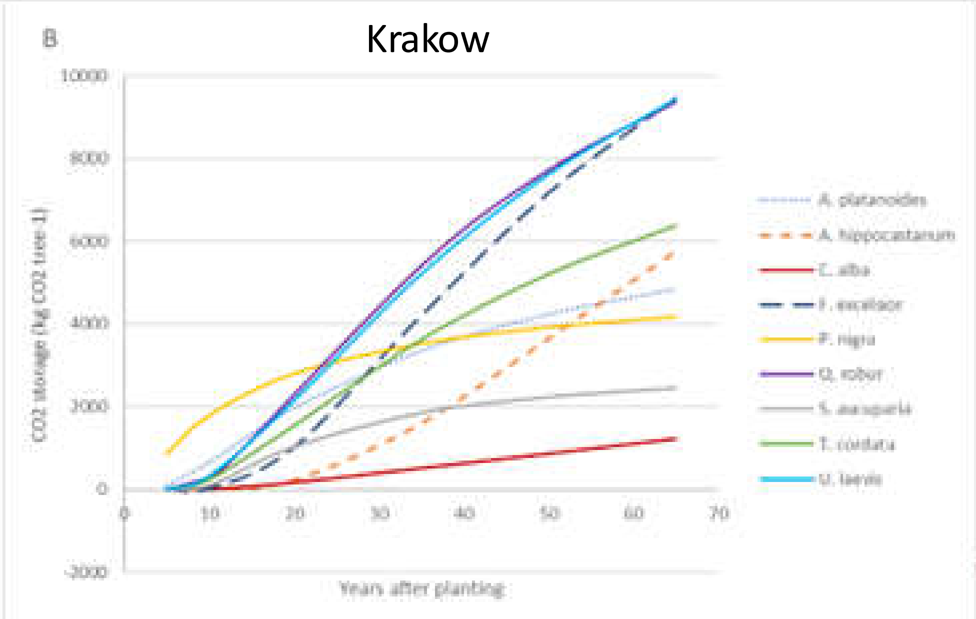
Krakow



Species			a	b	R2
			-34,2043	2,076399	0,839
Acer platanoides			-29,4897	1,965524	0,947
Aesculus hippocastanum			-117,059	3,2689	0,93
Fraxinus excelsior			-63,7319	2,794103	0,639
Populus nigra			-25,2792	1,930312	0,957
Quercus robur			-49,9971	2,628975	0,715
Sorbus aucuparia			-40,8968	1,828555	0,95
Tilia cordata			-50,5123	2,648696	0,95
Ulmus laevis			-51,7651	2,845154	0,893
Pinus nigra			-33,6061	2,166258	0,951

CO_2 storage in Rimini and Krakow





In Rimini, the CO_2 stored by a tree over a 65 years life-cycle ranged from 1750 kg CO_2 (*A. hippocastanum*) to 7203 kg CO_2 (*P. x acerifolia*)

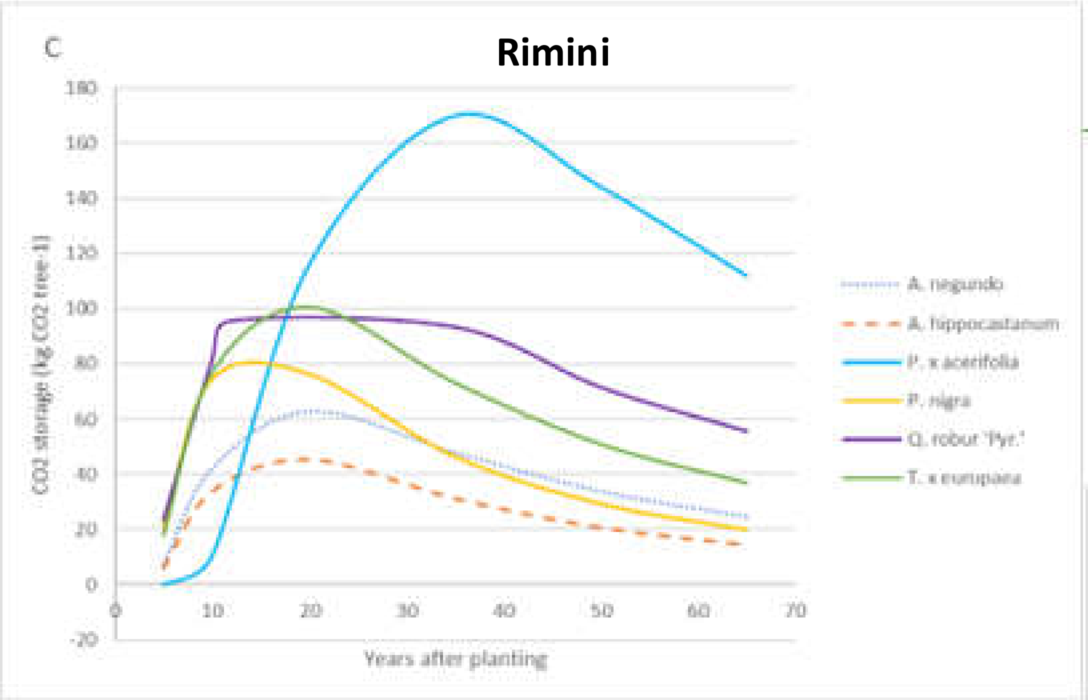
Q. robur ‘Pyramidalis’, *T. x europaea*, and *P. nigra* stored more CO_2 than P. *x acerifolia* within 30 years from planting

In Krakow, the CO_2 stored by a tree over a 65 years life-cycle ranged from 1230 kg CO_2 (*Cornus*) to about 9350 kg CO_2 (*F. excelsior, Q. robur, U. laevis*)

P. nigra stored more CO_2 than other species within 20 years from planting

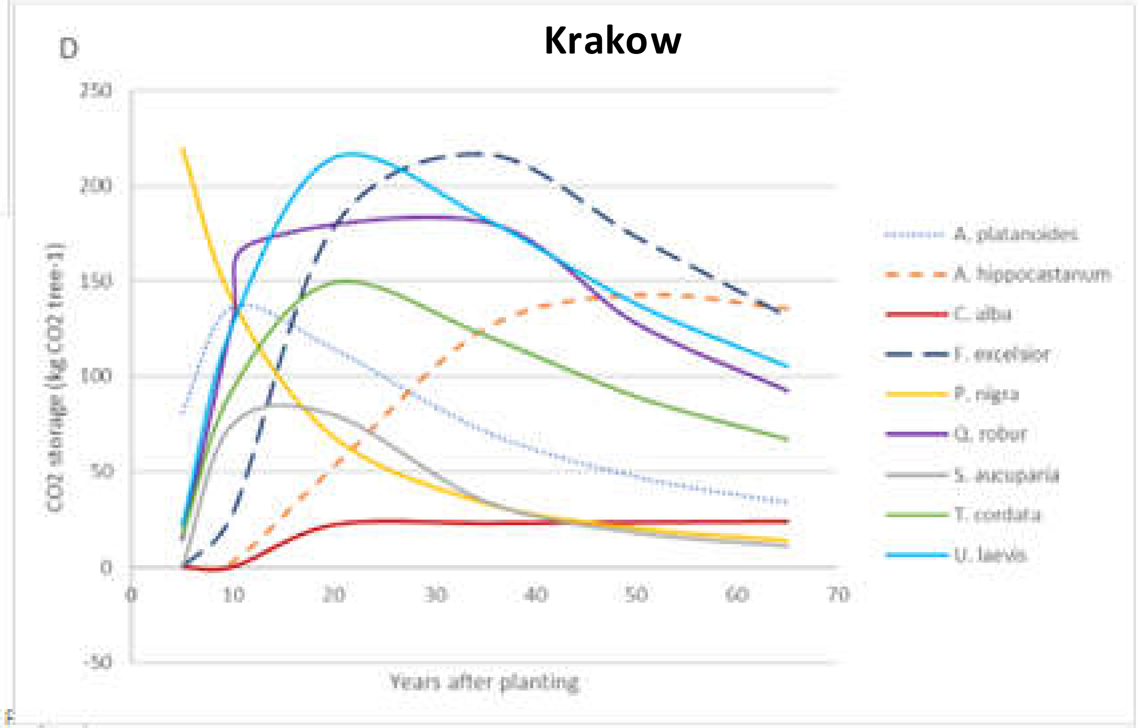
CO_2 sequestration in Rimini and Krakow

Annual CO_2 sequestration in the two cities ranged from 20 to about 220 kg CO_2 per year

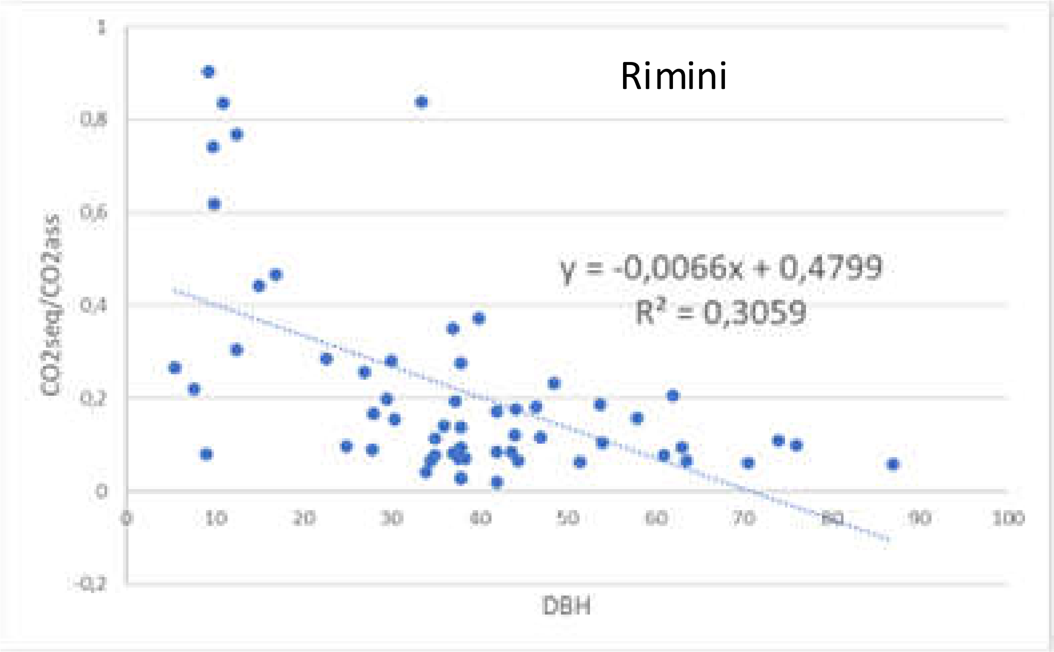


CO_2 sequestration depends on species and plant age

The peak of CO_2 sequestration may be related to tree longevity (e.g. short-lived species like poplar peak early; long-lived species like oak, London plane and ash showed delayed or long-lasting peak)



CO_2 sequestration vs. CO_2 assimilation

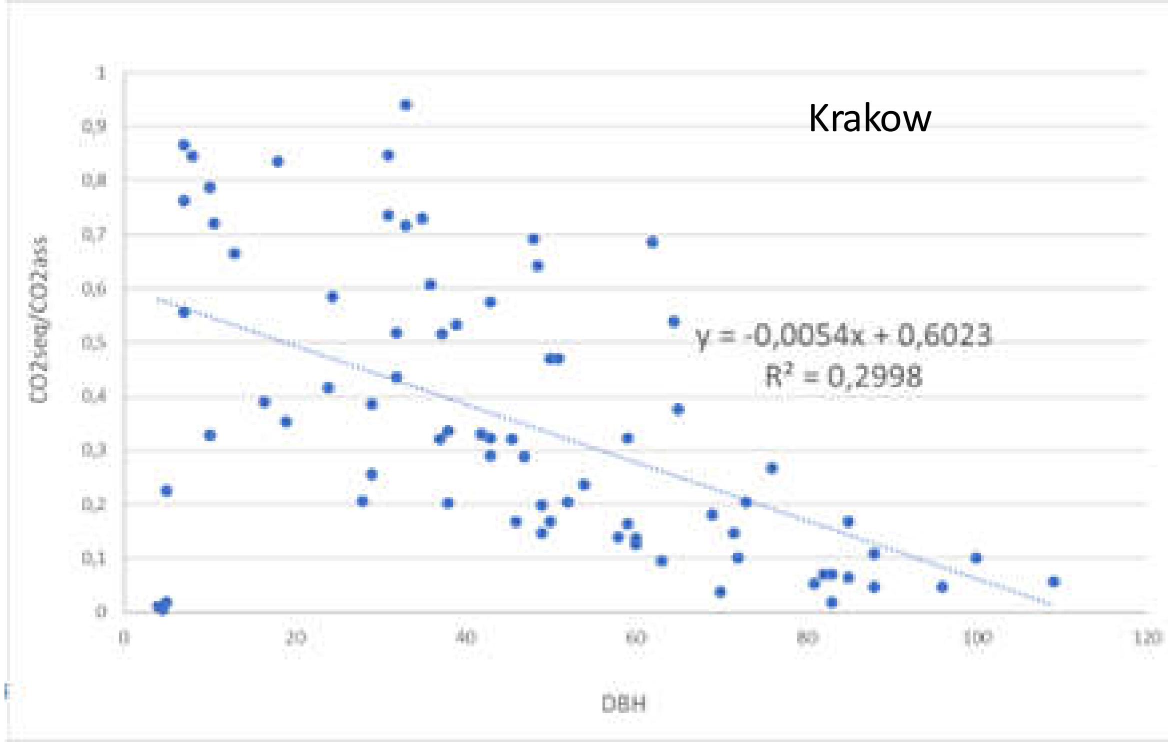


The ratio between CO_2 sequestration and CO_2 assimilation negatively scaled with DBH

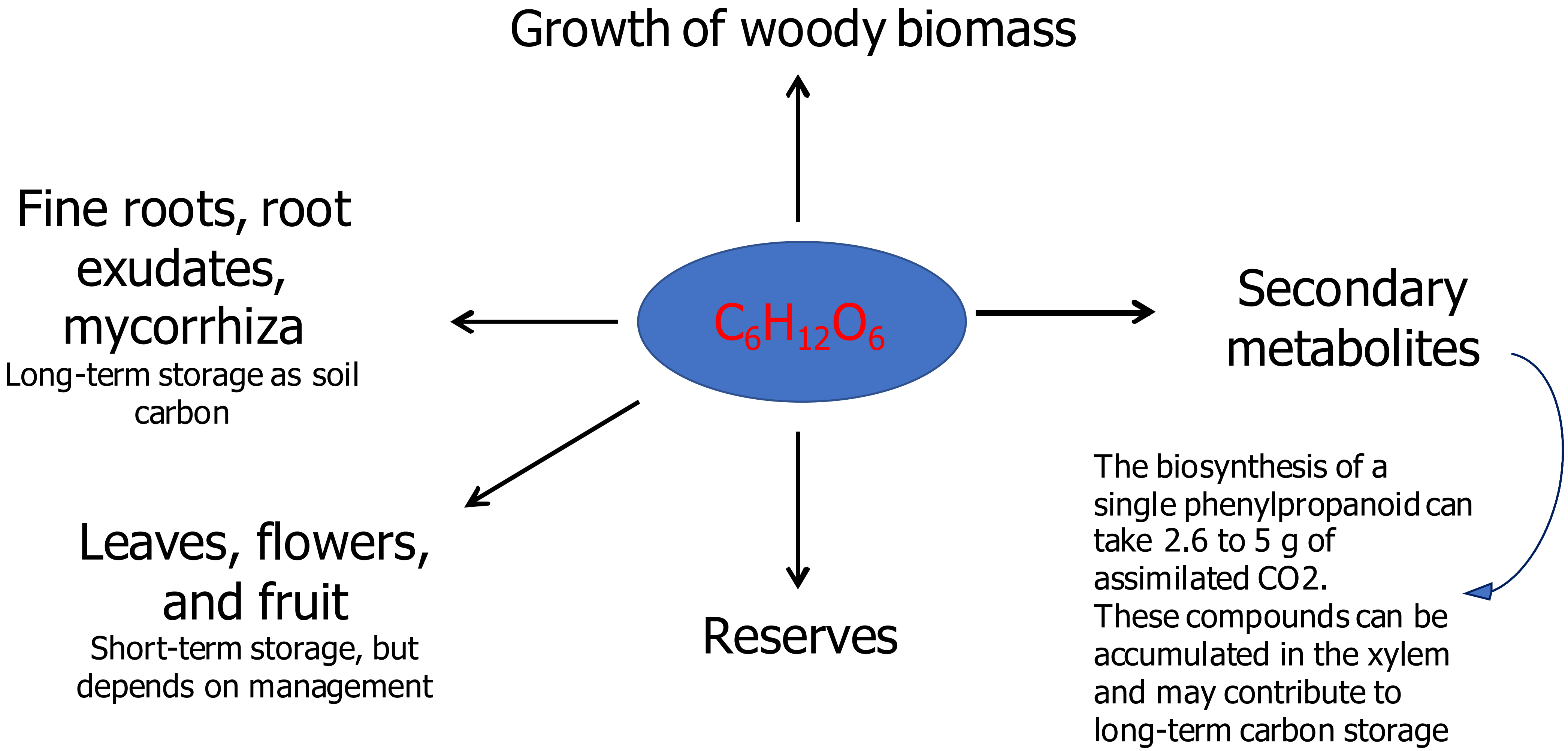
The amount of assimilated CO_2 allocated to woody growth is affected by plant age

Newly established trees allocated 48% (Rimini) to 60% (Krakow) of photosynthates to growth

Late mature trees, instead can allocate less than 10%



Fate of assimilated CO_2



Growth of woody biomass

$C_6H_{12}O_6$

Fine roots, root exudates, mycorrhiza

Long-term storage as soil carbon

Secondary metabolites

Leaves, flowers, and fruit

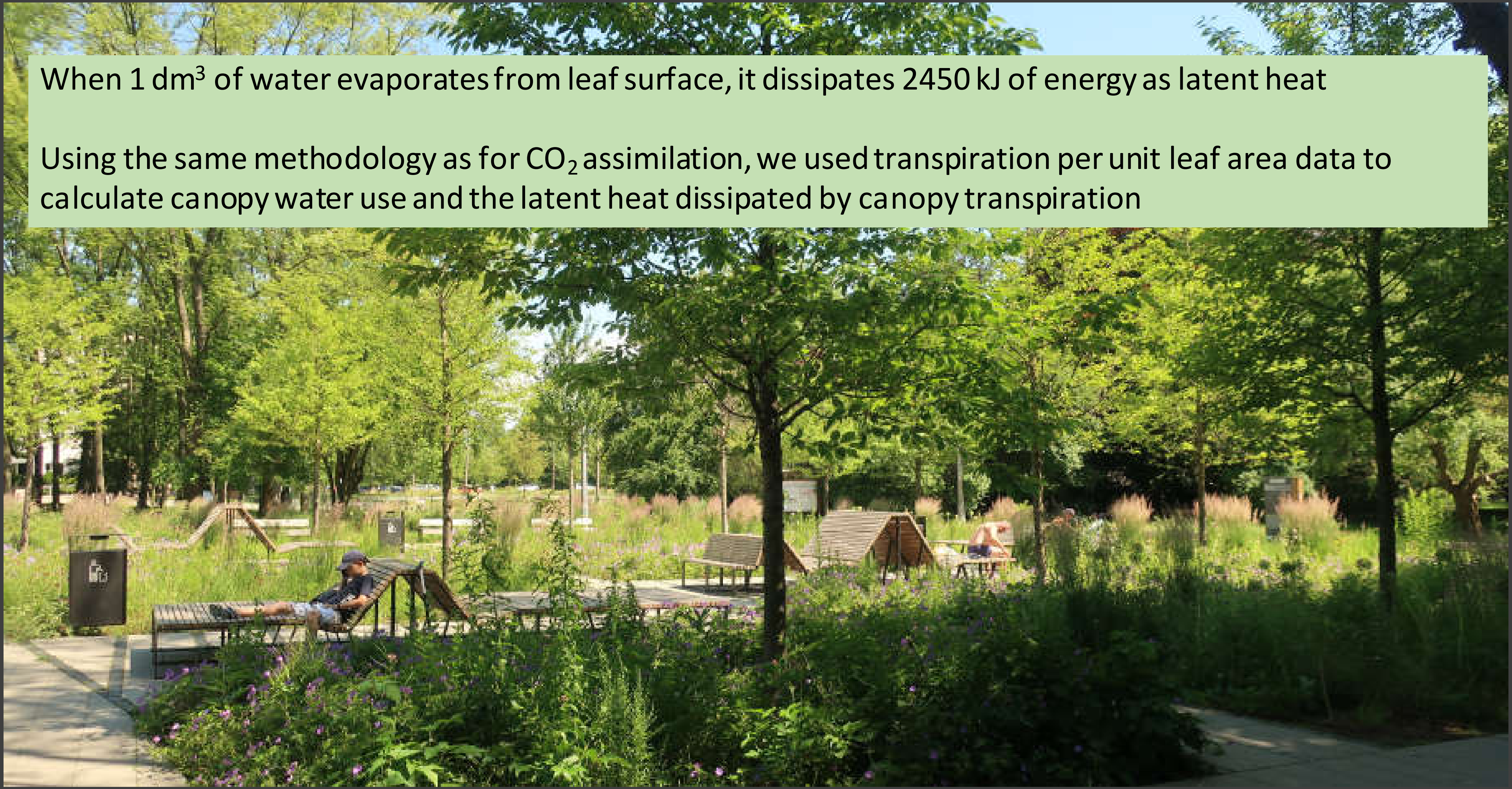
Short-term storage, but depends on management

Reserves

The biosynthesis of a single phenylpropanoid can take 2.6 to 5 g of assimilated CO2.
These compounds can be accumulated in the xylem and may contribute to long-term carbon storage

Herms e Mattson, 1992, The Dilemma of plants: to grow or to defend. Quat. Rev. Biol., 67(3): 283-335

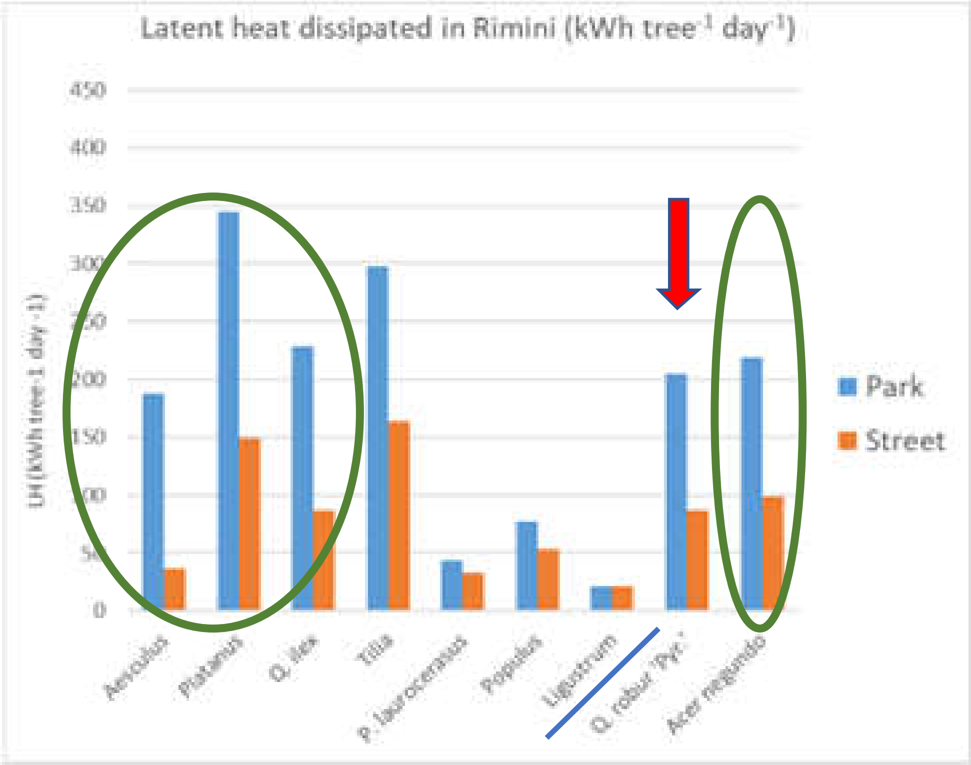
Cooling by transpiration

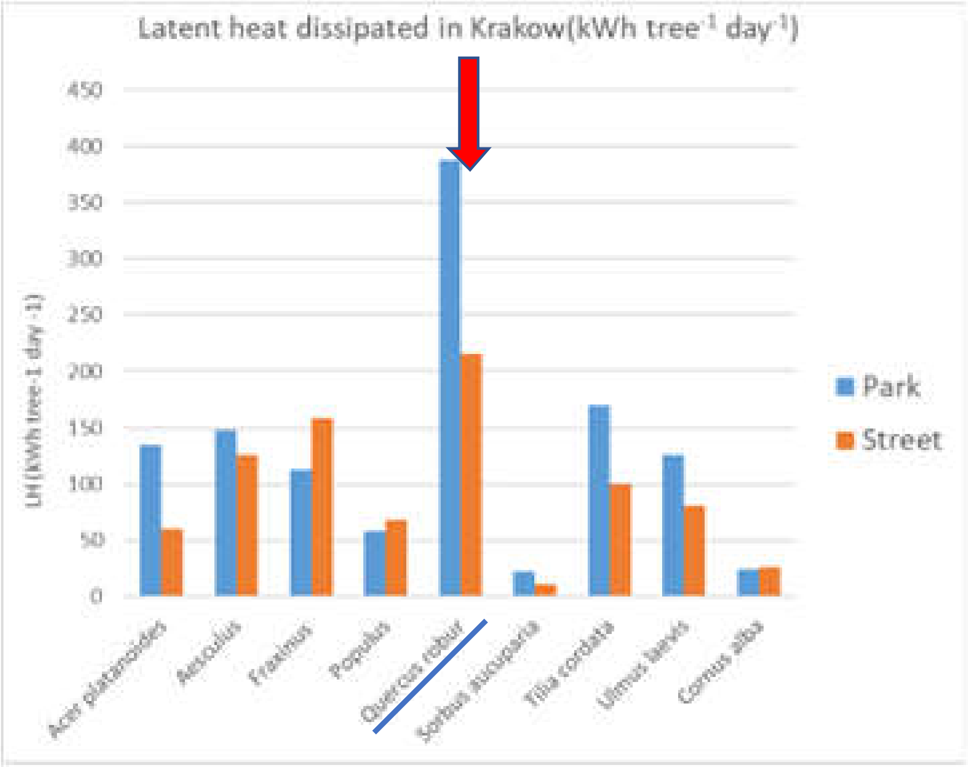


When 1 dm^3 of water evaporates from leaf surface, it dissipates 2450 kJ of energy as latent heat

Using the same methodology as for CO_2 assimilation, we used transpiration per unit leaf area data to calculate canopy water use and the latent heat dissipated by canopy transpiration

Latent heat dissipation by individual trees 30 years after transplant





On average, a tree planted 30 years ago accounted for 1,8 air conditioning devices (min. *Ligustrum* in Rimini = 0,31; max *Q. robur* in Krakow = 5,8)

More intense pruning (often topping) in streets, particularly in Rimini, reduced the cooling benefit, with higher impact on species with broad canopies

Cultivars with narrow canopies cool less than those with broad canopies

Air quality amelioration (Particulate Matter)

sustainability

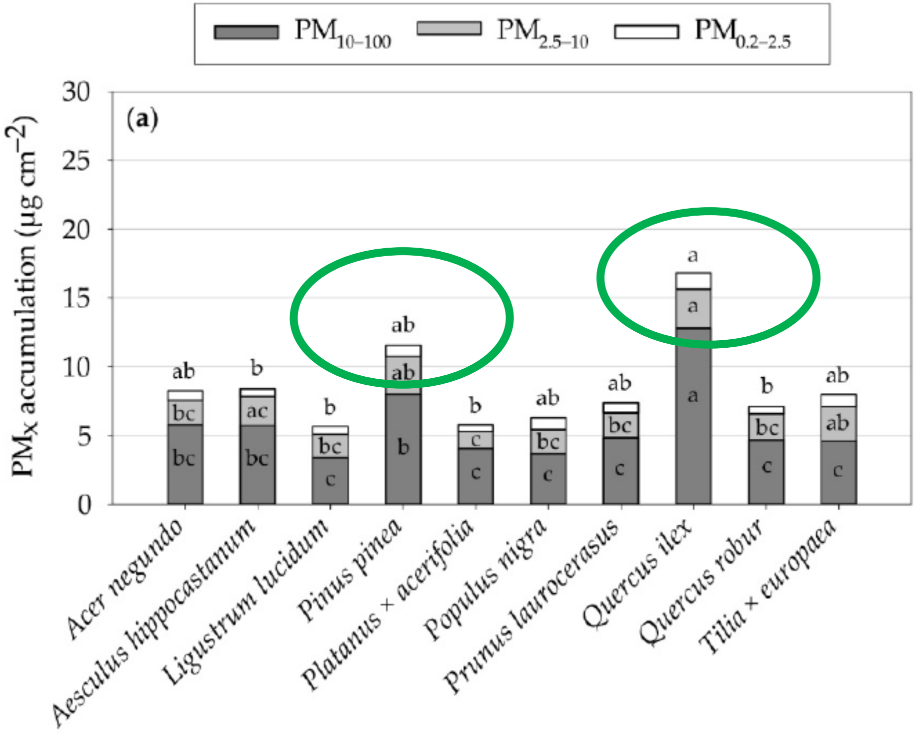
MDPI

Article

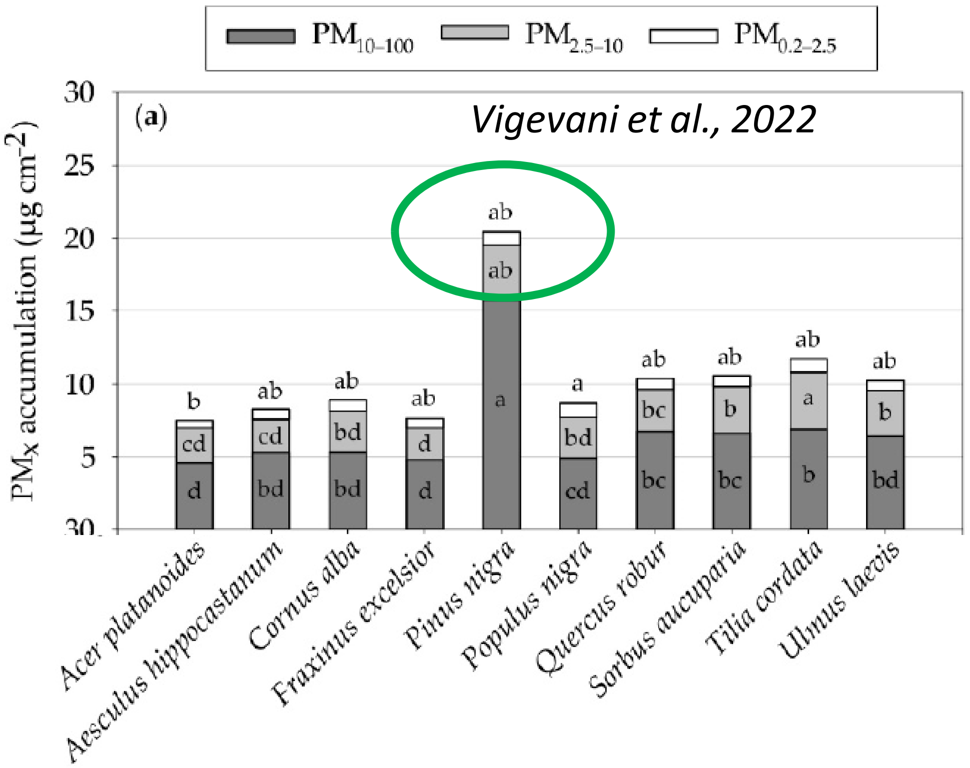
Particulate Pollution Capture by Seventeen Woody Species Growing in Parks or along Roads in Two European Cities

Irene Vigevani [1,2,3,*], Denise Corsini [2], Jacopo Mori [2], Alice Pasquinelli [4], Marco Gibin [1], Sebastien Comin [1], Przemysław Szwałko [5], Edoardo Cagnolati [6], Francesco Ferrini [2] and Alessio Fini [1]

PMx accumulation per unit leaf area



RIMINI



Vigevani et al., 2022

KRAKOW

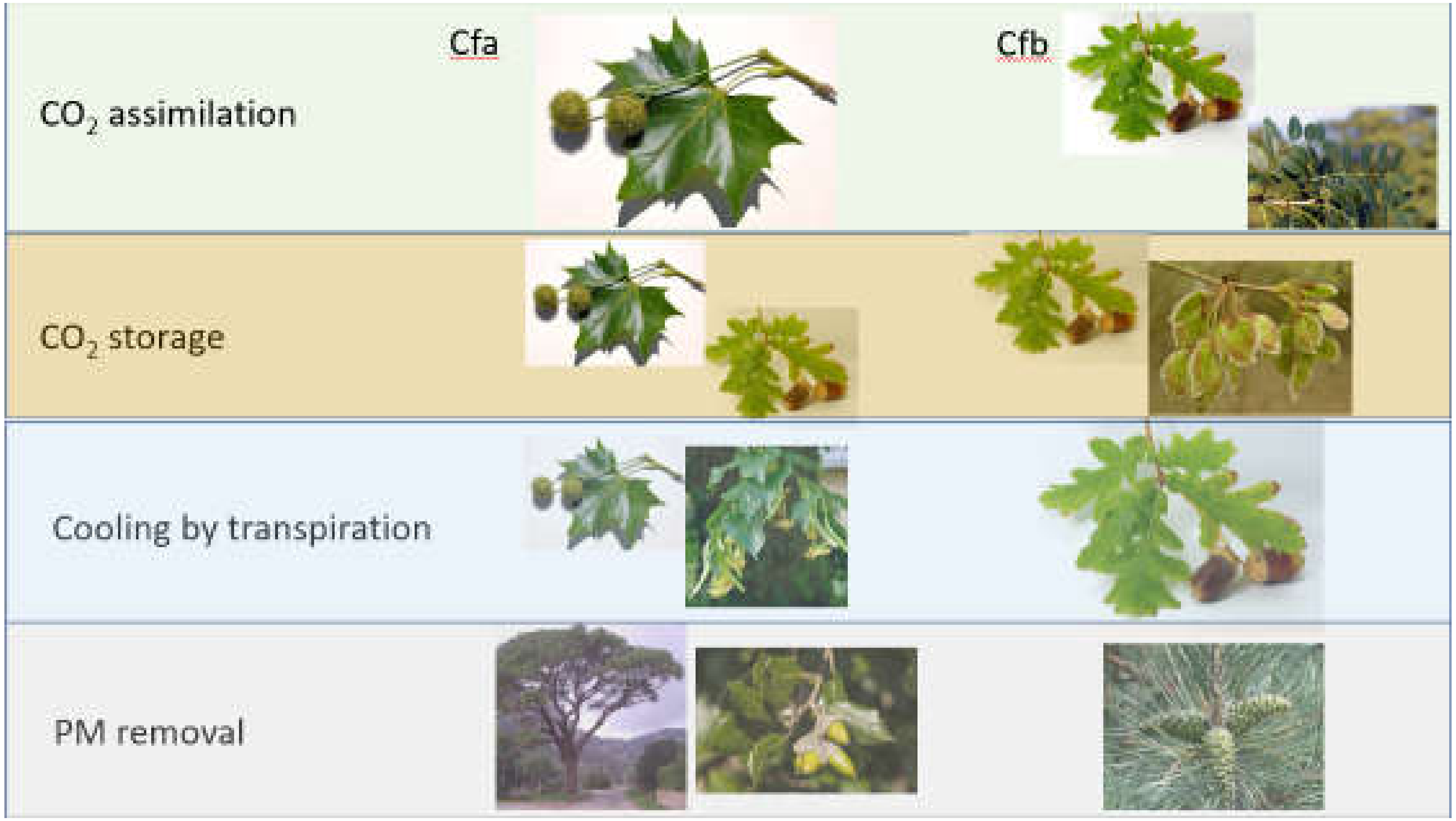
Vigevani et al., 2022

Conclusions

- We used a hybrid model supported by extensive field measurements to apply plant ecophysiology to ES quantification.
- Urban vegetation may contribute more to CO2 removal than previously expected
- ES delivery per unit leaf area, total leaf area, and plant size at maturity are key determinants of ES
- Do not top or over-prune trees: that will greatly reduce the benefits, particularly in trees with broad canopies

Conclusions

- Species selection affected ES delivery



- **Don’t forget species diversity (e.g. 30-20-10 or 5% rules)**

Thanks for your attention

UNIVERSITÀ
DEGLI STUDI
DI MILANO

LIFE URBANGREEN

With the contribution of the LIFE Programme of the European Union
LIFE17 CCA/IT/000079

www.lifeurbangreen.eu