EPFL

CIVIL-309: URBAN THERMODYNAMICS

Assist. Prof.
Dolaana Khovalyg

Lecture 09:

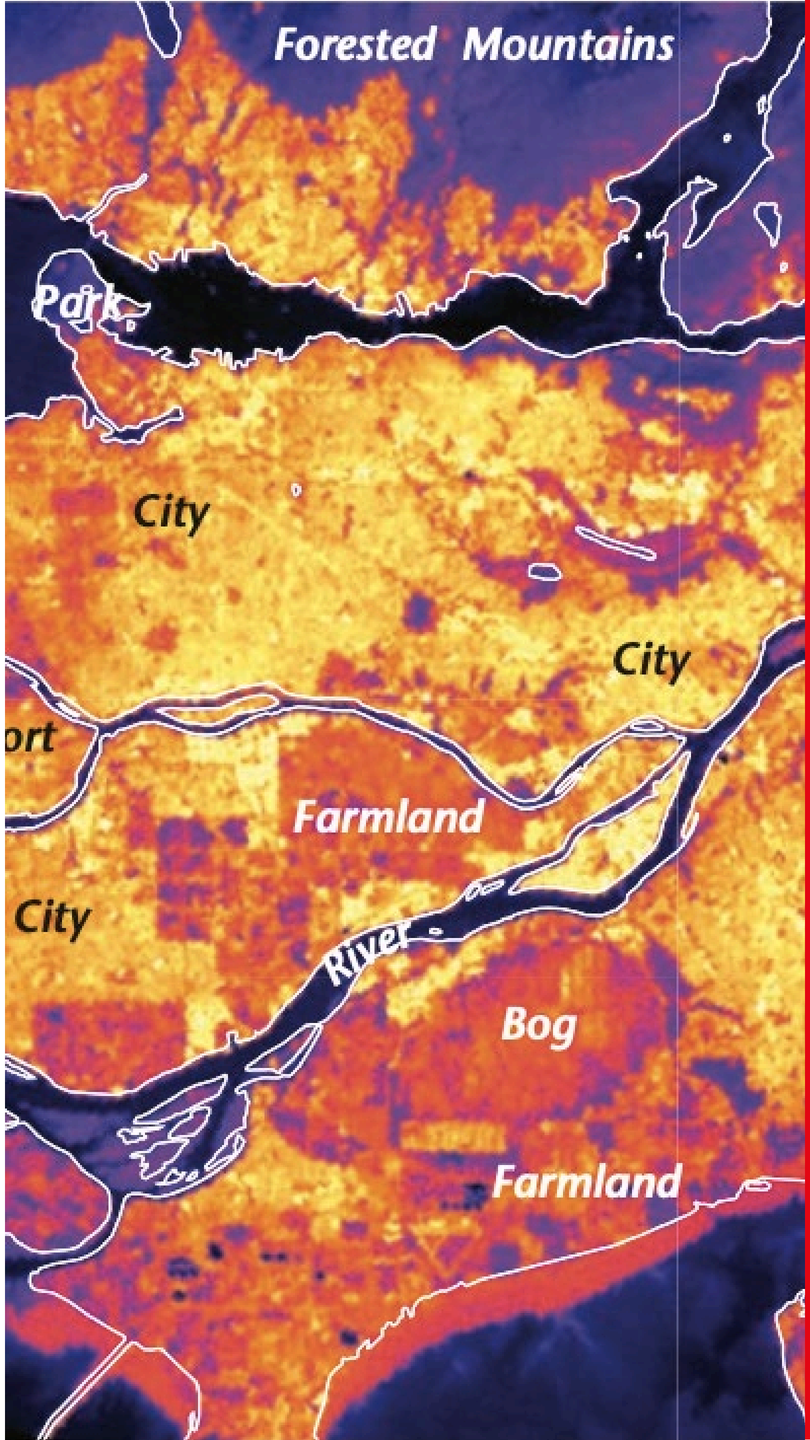
Vegetation-Environment Interaction

28 November 2025

EPFL

Course Schedule

7	24.10		**BREAK**	
8	31.10	1 x 45'	**Urban modeling and computational tools**	JY
		1 x 45'	Introduction to the web tool **CityTherm** (part II)	JY
		1 x 45'	**Introduction to the course project II**	JY
9	07.11	2 x 45'	**Building-environment interaction:** thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
10	14.11	2 x 45'	**Ground-environment interaction:** ground properties, thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
11	21.11	2 x 45'	**Water body - environment interaction**: thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
12	28.11	2 x 45'	**Vegetation – environment interaction:** characteristics of vegetation, evapotranspiration, aero- and thermal interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
13	05.12	2 x 45'	**Human Outdoor Comfort:** Parameters affecting human comfort and comfort indices (UTCI, PET)	JY
		1 x 45'	**Supervised group work - course project II**	JY
14	12.12	1 x 45'	~~Climate-Sensitive Urban Design: complex interaction of all urban … ments and their effect on UHI and outdoor comfort~~ ⚠ Supervised group work on Project II (**no lecture**)	DK
		2 x 45'	**Supervised group work - course project II**	JY
15	19.12	3 x 45'	Supervised group work on the course project II **Course project II submission deadline: 16:00 on December 19**	DK, JY



CONTENT:

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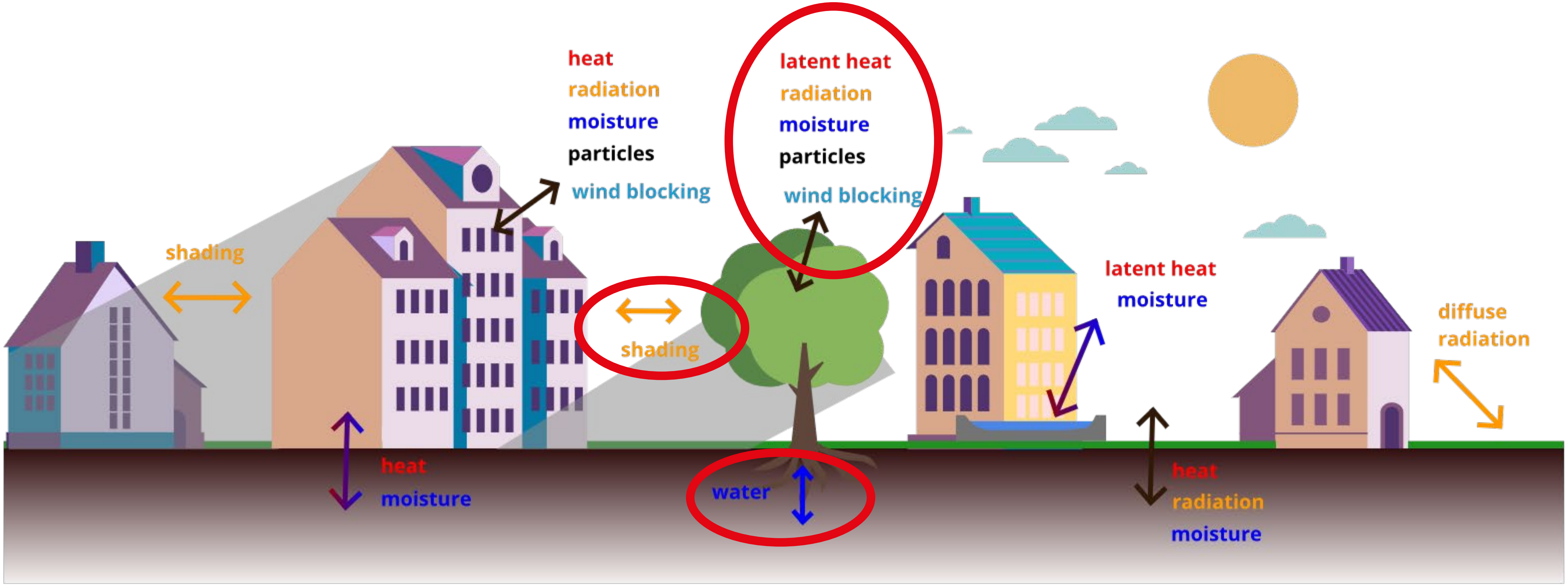
Vegetation - Environment Interaction: Introduction

- **Vegetation** has a *complex dynamic interaction* with the **atmosphere** above it. This is influenced by its interaction with the **ground** (it takes water supply from the ground).
- Vegetation interacts *indirectly* with the *other elements* of the urban environment through **shading**.
- Vegetation blocks the wind, receives radiation from the Sun and dissipates the heat absorbed by via **sensible heat**, **latent heat,** and the release of **moisture**.



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Cities and Urbanism: Urban Scales

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Microscale — Local scale — Mesoscale

Length: 10^0 (1 m) — 10^1 (10 m) — 10^2 (100 m) — 10^3 (1 km) — 10^4 (10 km) — 10^5 m (100 km)

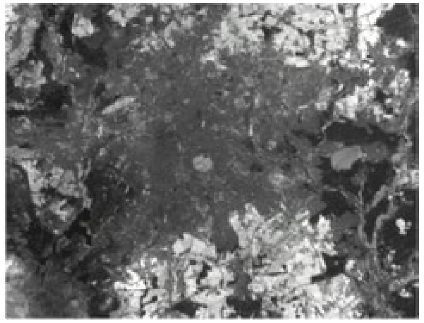
Facet

Building

Block

LCZ/Neighbourhood

City



Street canyon

- **Homogeneity** vs. **heterogeneity** of urban properties (the *smallest* homogeneous urban unit – *an urban block*)
- Spatially, something **homogeneous** at a *one length scale* might be **heterogeneous** *at another* (3D vs 1D treatment of atmospheric properties at the building scale and city scale)

Vegetation - Environment Interaction: Introduction

- **Green infrastructure (GI)**: "*the strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services*" (European Commission 2013).
- **Green infrastructure characteristics**:
  - A network of different ecological systems (natural and artificial)
  - Can be implemented at different spatial scales
  - Able to provide a wide set of services
- **Green infrastructure typologies** have different effects, spatial and time span
- **Green infrastructure** must be *diversified* and *spatially distributed*

Synthesis of the contribution of green infrastructure to regulating air temperature at different spatial scales:

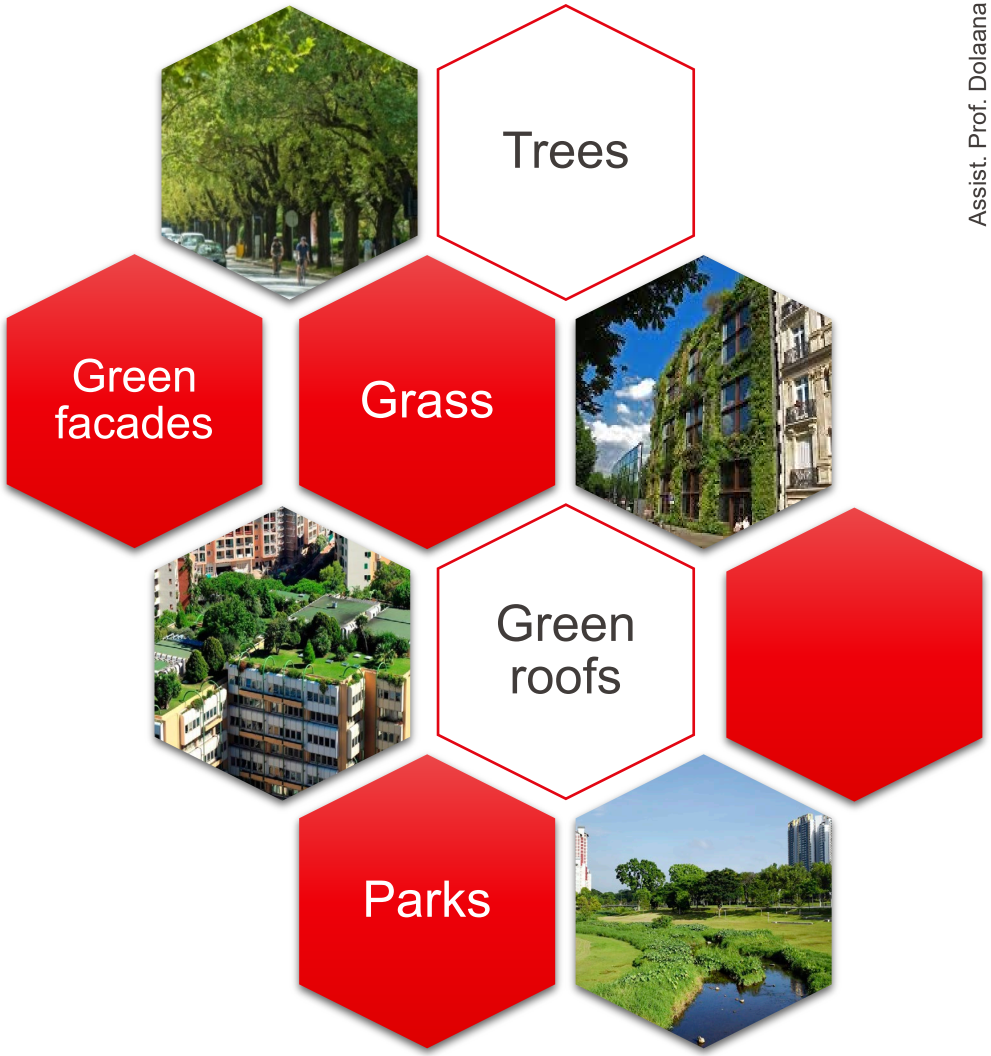
Parameter	Tree cover	Urban parks	Green roofs	Vertical greenery system
Mechanisms of air temperature regulation				
Reduction of reflected solar radiation	+	++	+	
Provision of the shade	++	+		+
Cooling by evapo-transpiration	++	++	+	+
Regulation of wind speed	+	++		+
Spatial scale				
Urban	++	++		
Local	++	++	+	
Building	+		++	++

Source: Palme, Urban microclimate modelling for comfort and energy studies, p. 407

UHI mitigation using vegetation

- **Urban vegetation** is an important source of **evaporation** and **shading** (only trees) contributing to reduction of the UHI effect. The magnitude of the UHI mitigation effect depends on *the amount of green space*, its *size*, *shape* and *distribution*, and its *composition*.

- **Vegetation contributes to 2 out of 3 Urban Heat Island (UHI) mitigation strategies***:*
  1. **Reduction** of the **absorbed solar radiation** by **shading:**
     - Radiative temperature decreases
     - Improvement of outdoor thermal comfort
  2. Increase of **the latent heat** and take advantage of **evaporative cooling of air** on vegetated and water areas (the most effective and less costly strategy)
  3. Reduction of the amount of sensible heat stored by selecting materials or paintings with higher albedo



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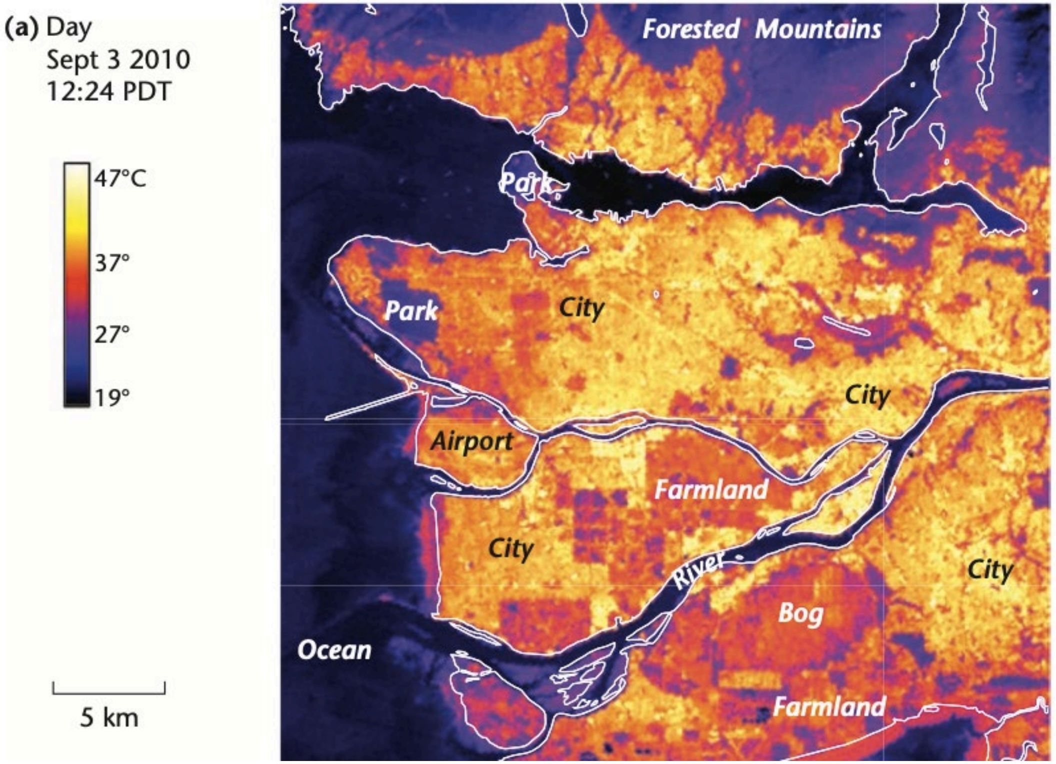
UHI mitigation using vegetation

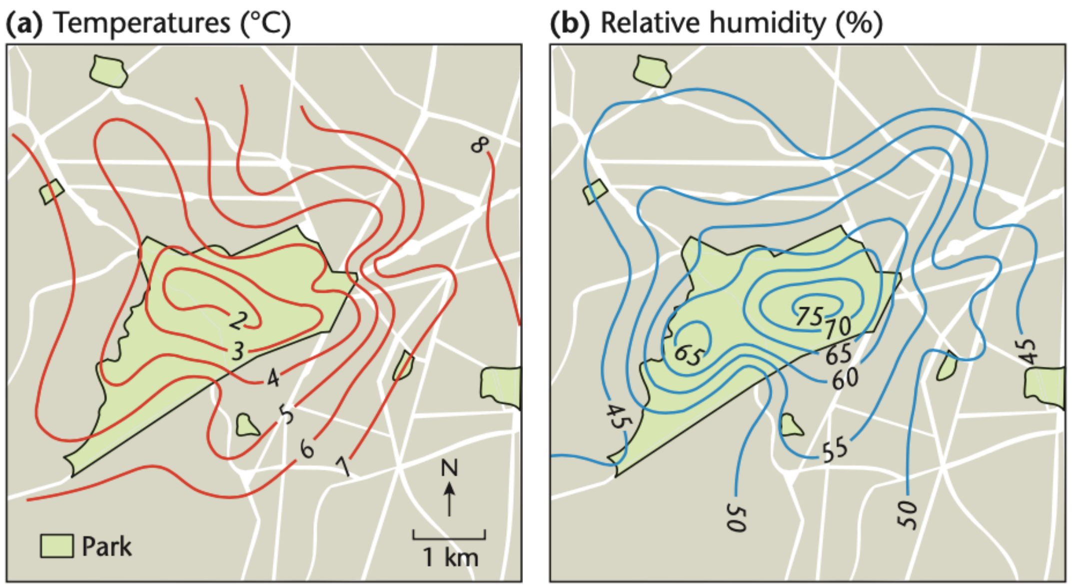
- **City-scale**: city is a unit with no distinction between its components.
- Reduction in air temperature at city-scale correlated with percentage of areas with **plant cover**.
- **Trees** are the *most effective* type of plants for UHI mitigation.
- There is a strong *correlation* between **surface temperature** and **plant cover**.
- For dry cities, there is a trade-off between using vegetation and irrigating it and making *alternative uses of water*. Greater water shortage in the future is expected.
- Vegetation submitted to **water shortage** is useless for temperature regulation.



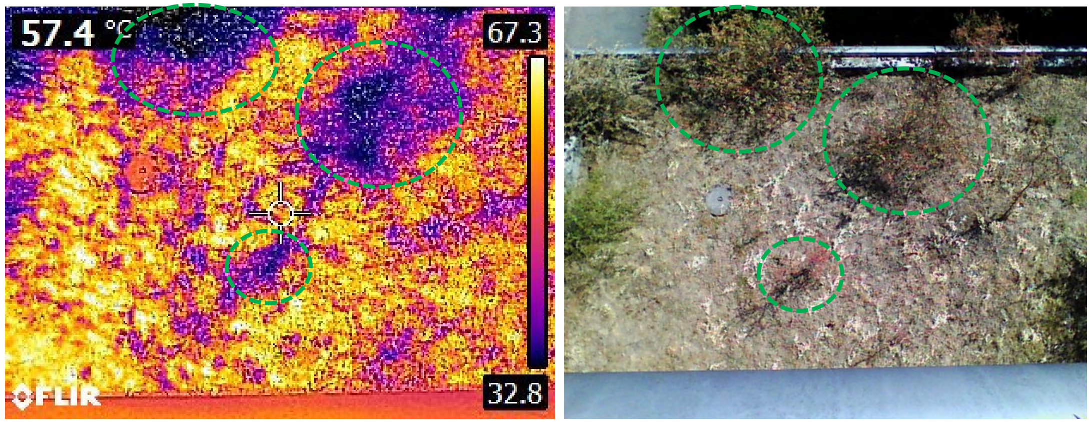
Source: Oke, Urban Climates, p. 207

UHI mitigation using vegetation: Local effect

- Vegetation affects the surrounding urban area *locally as* its effect is **spatially limited**.
- Large scale **urban parks** over $10\ ha$ can have an average **1-2°C temperature drop** on the surroundings that are ~*350 m away.*
- Urban **penetration of vegetation effect** is not only dependent on the park characteristics but also on the *morphology of the surroundings*. Surroundings with plants and grass cover are more impacted by parks.
- For urban penetration, *several smaller distributed parks* are preferable to a *few large* isolated parks.
- *Individual pieces* of vegetation have *weak local effect*. Large parks have larger influence (together with water bodies), they heat slower (due to the higher thermal inertia).



Source: Oke, Urban Climates, p. 439



Trees at the EPFL campus, August 2022 (noon), RGB and IR pictures taken from the roof

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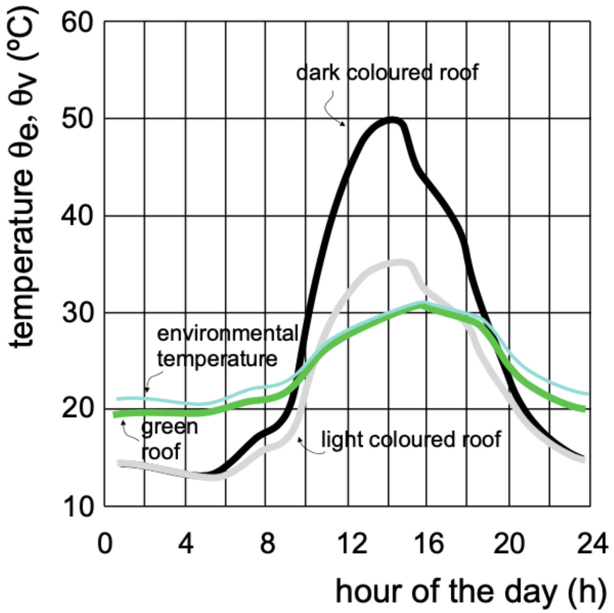
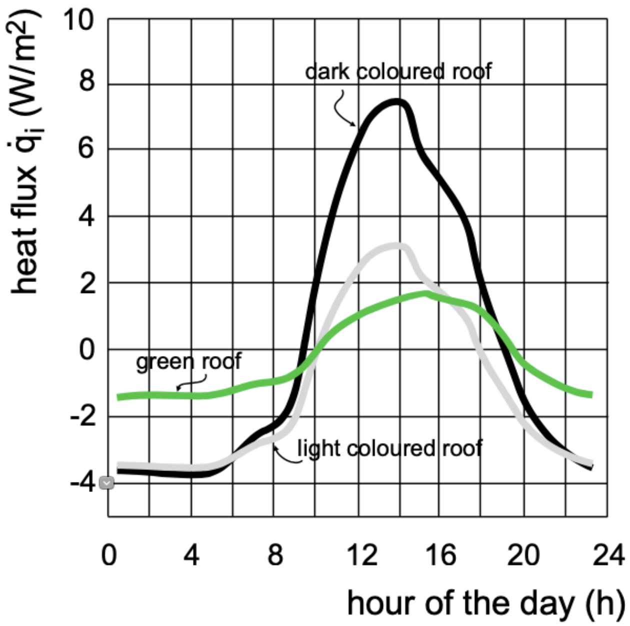
UHI mitigation using vegetation: Buildings

- **Greening buildings** have the advantage of decreasing heat transfers in/out building by increasing their **thermal inertia**, provide them *shading*, retain *precipitation*.
  - They improve buildings energy efficiency
- Although disputed, green buildings also have an impact on the **urban microclimate** by **increasing evapotranspiration in summer**.
  - It results in lower air temperature and increased air moisture, hence decreasing heat captured and stored in buildings.
- **Plant species** must be chosen **according to the desired effect** in **a specific climate**.
  - Succulent, herbaceous, broadleaved with different colors *behave differently*.
- Plants like moss, grass and herbs ($LAI < 1$) are privileged because they don't require attention.





Source: Medved, Building physics, p. 69

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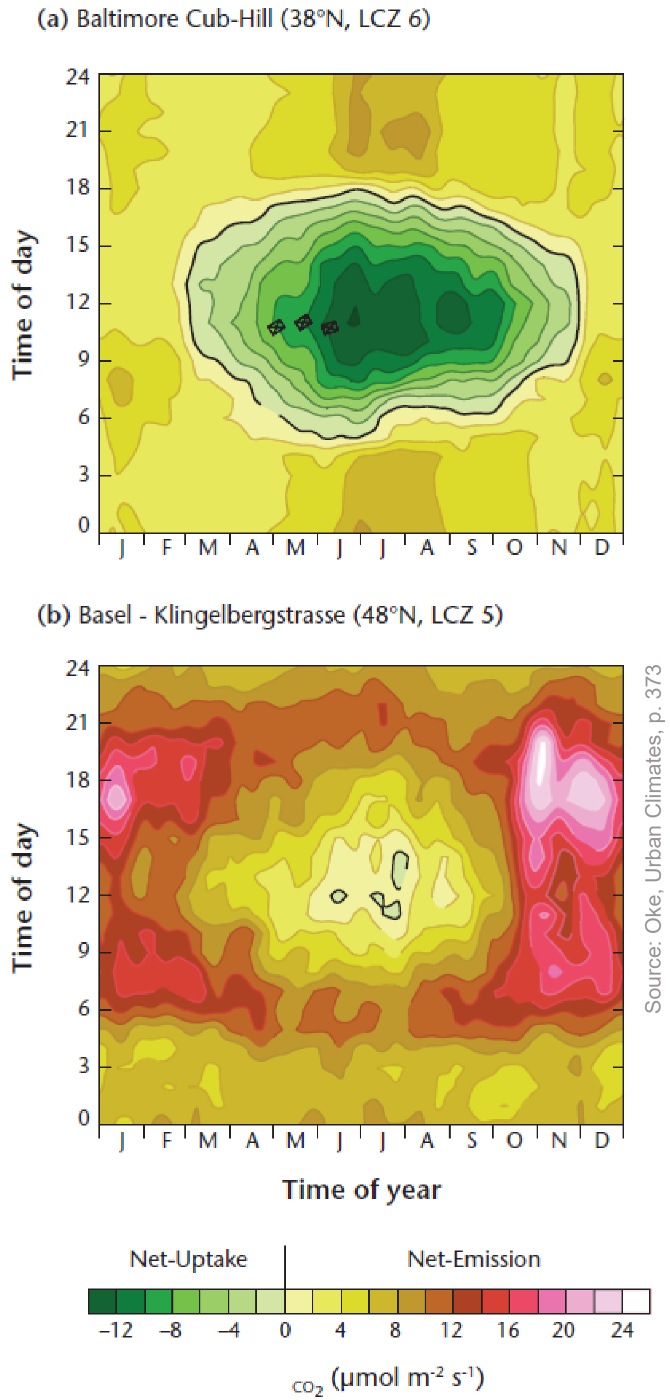
Vegetation and Air Quality

- Leaves *exchange* **gases** and **water vapor** with the ambient atmosphere.
- Vegetation is a **sink** or **source** of CO_2 proportional to vegetation density.
- **Healthy mature tree** in large canopy can *sequester* **~90 kg of carbon per year** while **a young tree** in a small canopy can sequester **only 2% of that**.

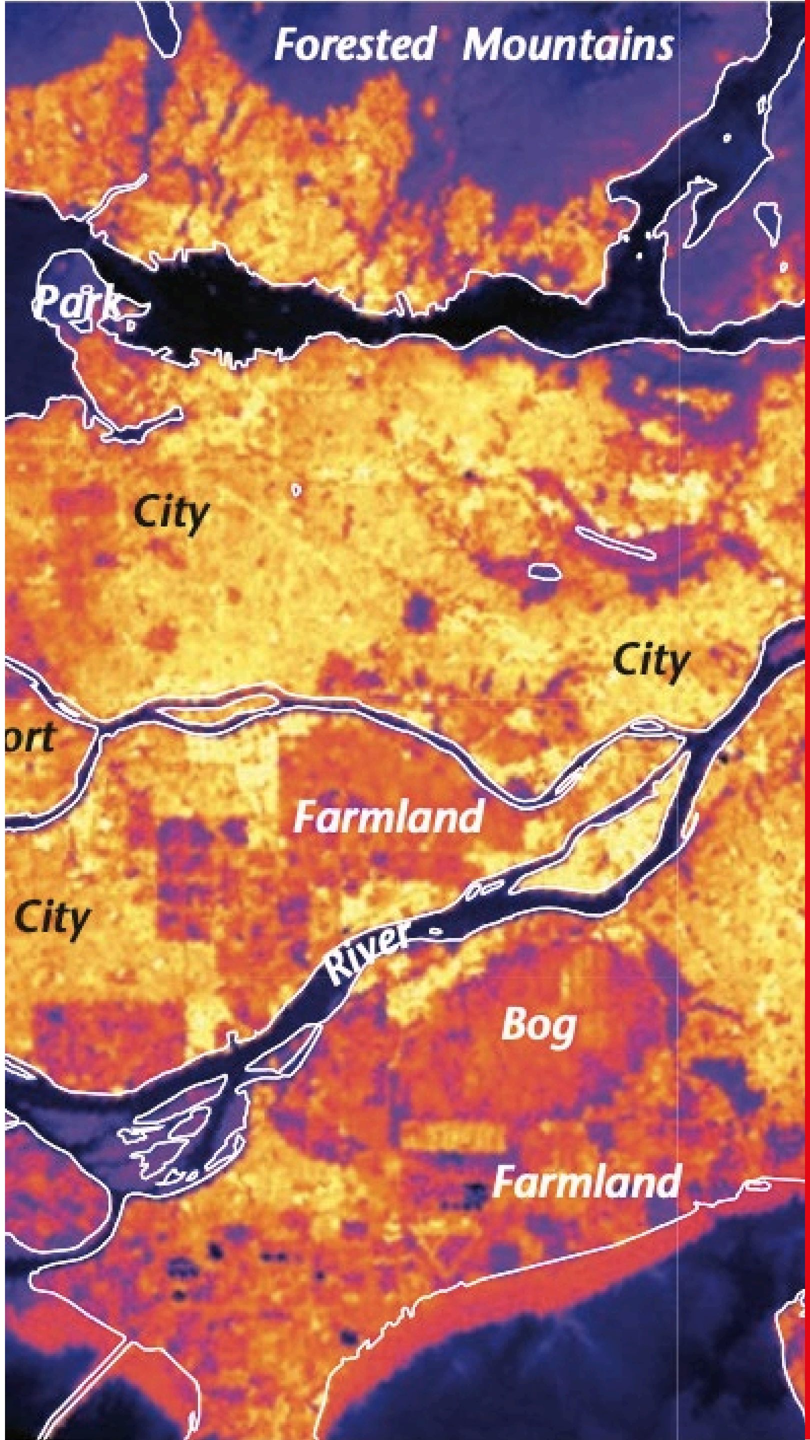
  Example: Chicago urban forest (50 million trees) sequesters 140,000 tons of carbon per year = one week emission by transportation.

- **Carbon emissions** are ***offset*** only **during summer** at **midday**.
- Vegetation absorb pollutants **but** they also **emit own pollutants** (pollen), creating unfavourable smog.

Source: webpage



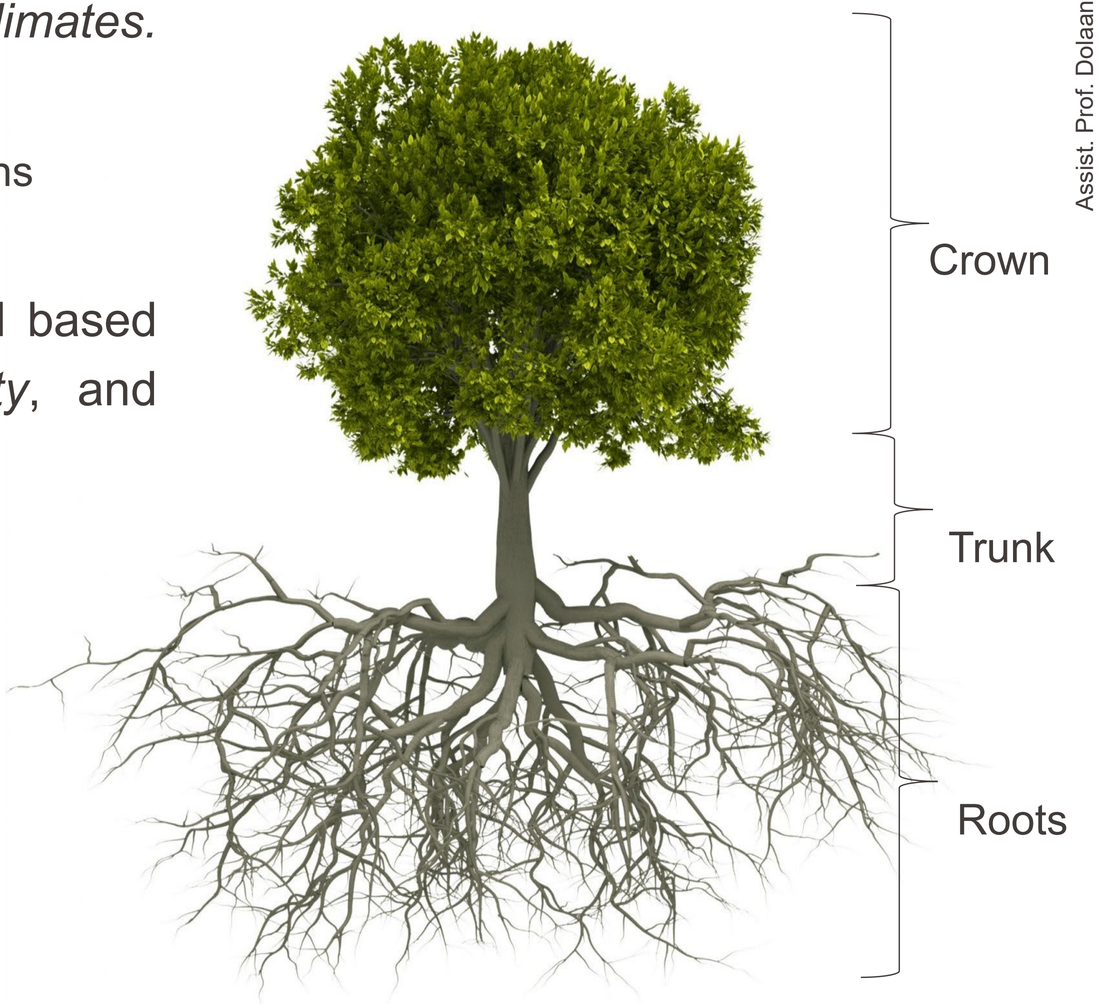
Source: Oke, Urban Climates, p. 373


Forested Mountains
Park
City
City
ort
Farmland
City
River
Bog
Farmland

CONTENT:

Vegetation: Characteristics

- Plant species are typically **adapted** to different *climates.* A major **climatic distinction** between species:
  - **Deciduous plants**: change their aspect with seasons
  - **Evergreen plants**: always keep the same aspect
- In *urban environment*, **the species are selected** based on their *tolerance to drought*, *poor air quality*, and *reduced light*
- It is better to choose plant species according **to the desired effect** (e.g., hedges and shrubs for wind shelter near ground)
- **Plant characteristics** depend on:
  - **Plant architecture**: canopy form, foliage density, branch and roots
  - **Plant physiology**: species, age, health



Vegetation: Leaf Characteristics

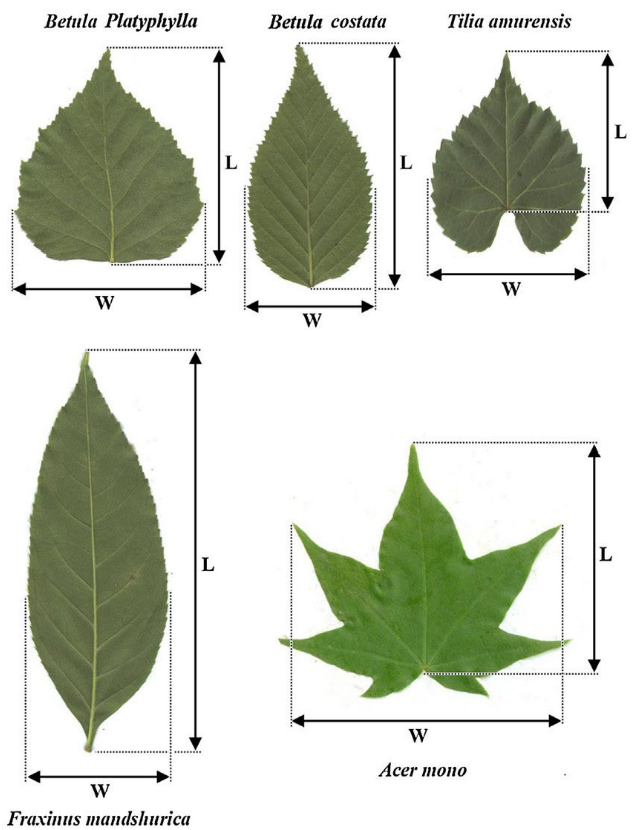
- **Leaves** are the *most active* elements of vegetation interacting with the surrounding atmosphere
- **Characteristic leaf size l** (m): average of the longest measure of a leaf length
- **Aerodynamic resistance r_a** $(\frac{s}{m})$: resistance opposed by the leaf to the wind flow

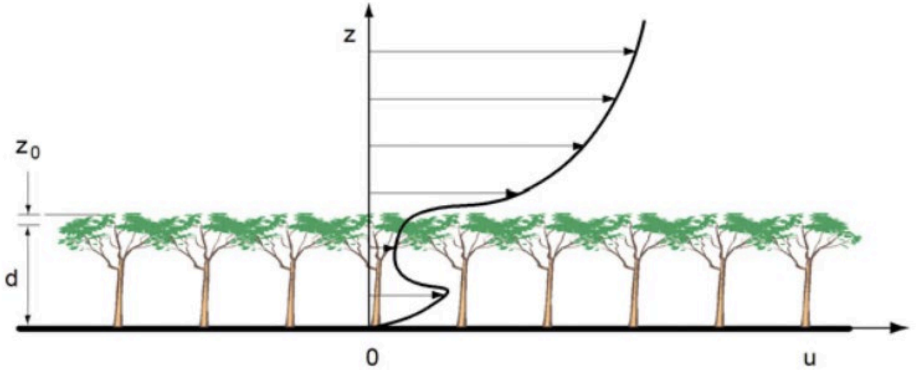
(9-1) $$r_a = C_d \cdot \sqrt{\frac{l}{|\bar{U}|}}$$

C_d – a leaf-specific constant (drag coefficient)
$|\bar{U}|$ - wind velocity magnitude (m/s)

- **Drag coefficient C_d** (-): dimensionless number that quantifies the resistance of an object in a fluid. Usually for trees, $C_d = 0.2$.

Images from: websource





Source: Rodrigues, Fondamental Principles of Environmental Physics, p.20

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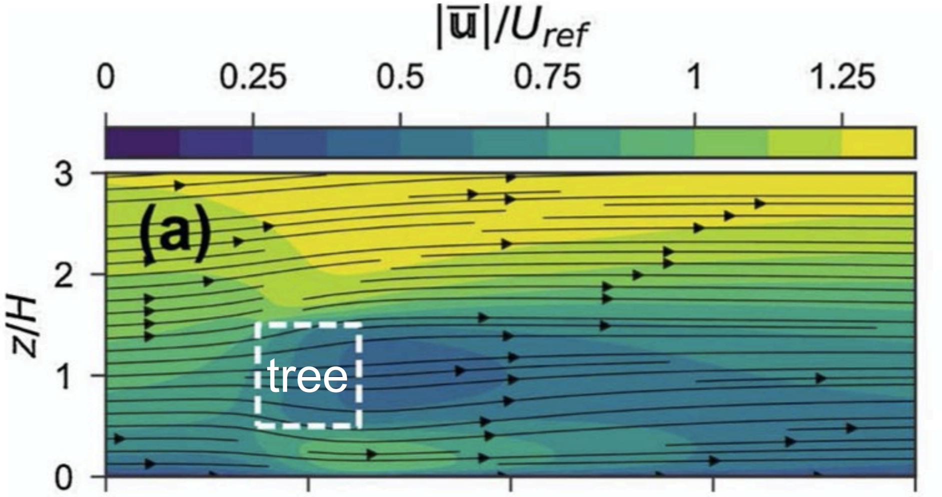
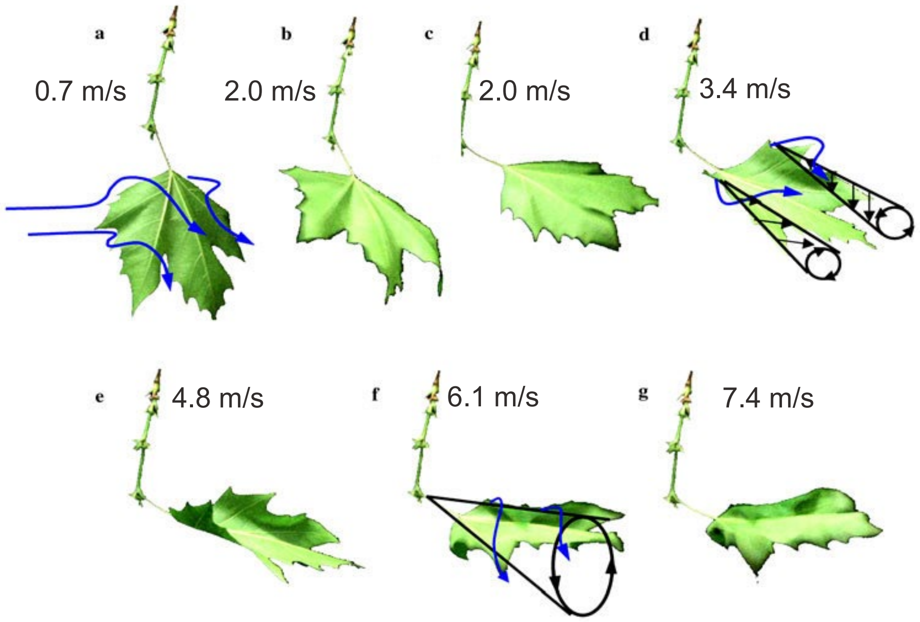
Vegetation: Aerodynamic Characteristics

- *Interaction of leaves* with *air flow* determines the **transport** and **mixing** of *various* **atmospheric parameters** (T, RH, pollution, pollen, CO2, etc.).
- Vegetation *reduces* the wind speed:
  - Trees: decrease wind speed by **~30%.**
  - Grass (h=0.5 m): decrease wind speed by **~12%.**
- **Vegetation** is **porous**: **airflow is *slowed down***, *not blocked,* leading to *more effective* and *extended* wake.
- Vegetation (e.g., tree leaves) *under the wind effect* tends to bend due to its **elasticity**, returning back to its initial position when the force is removed.
  - However, stiff parts of vegetation (e.g., branches, trunk) tend to break under strong winds (particularly gusts).
- The aerodynamic effect of vegetation is *spatially limited*, thus, has only *local effect*.
- **Ideally, the required type of vegetation** should *be selected* based on **the expected flow pattern** and **the urban neighborhood**.



Source: Manickathan et al. (2018) 10.1016/j.agrformet.2017.10.014



Wind induced deformation and vibration of a Platanus acerifolia leaf
Shao et al. (2012) DOI: 10.1007/s10409-012-0074-y

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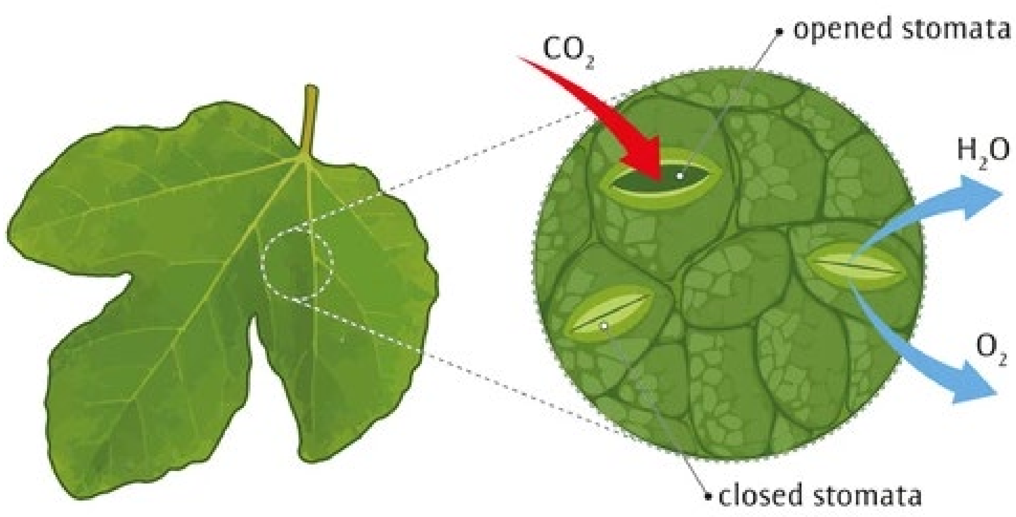
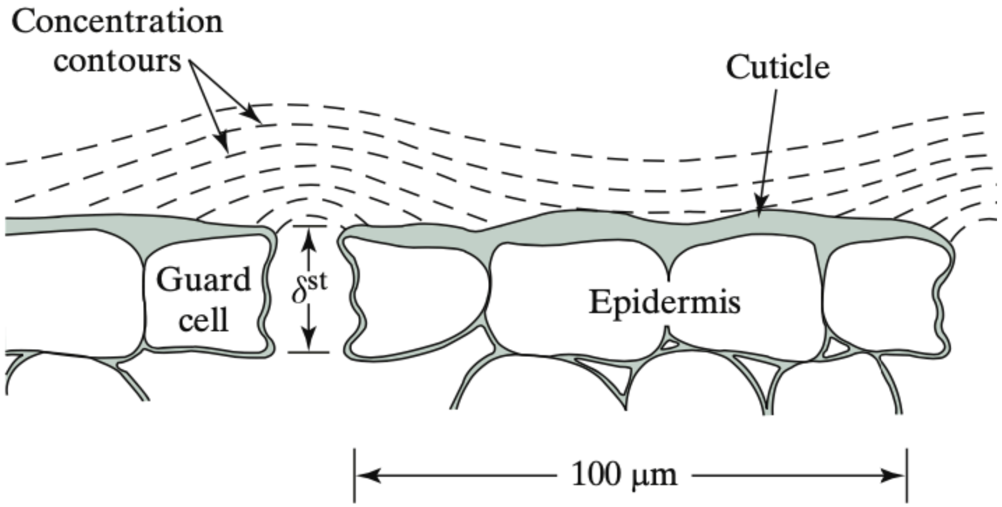
Vegetation: Leaf Characteristics

- **Stoma** or **stomate**: *pore* and *surrounding two guard cells* that form a pathway for gases and water vapour *in* and *out* the leaf.
- Stomata open to absorb atmospheric CO_2 for photosynthesis. The opening of the stomata induces the inevitable loss of water vapor (= **transpiration**).
- **Stomatal resistance r_s** ($\frac{s}{mm}$): describe *the opening state* of the stoma and its ability to exchange, for instance, water with the air.
- **Stomatal conductance g_s** ($\frac{mmol}{m^2 s}$): *inverse* of the stomatal resistance, expresses the rate of a matter exchange.
- The opening of the stomata depends on the exterior *climatic conditions*. Stomata close in hot dry conditions.

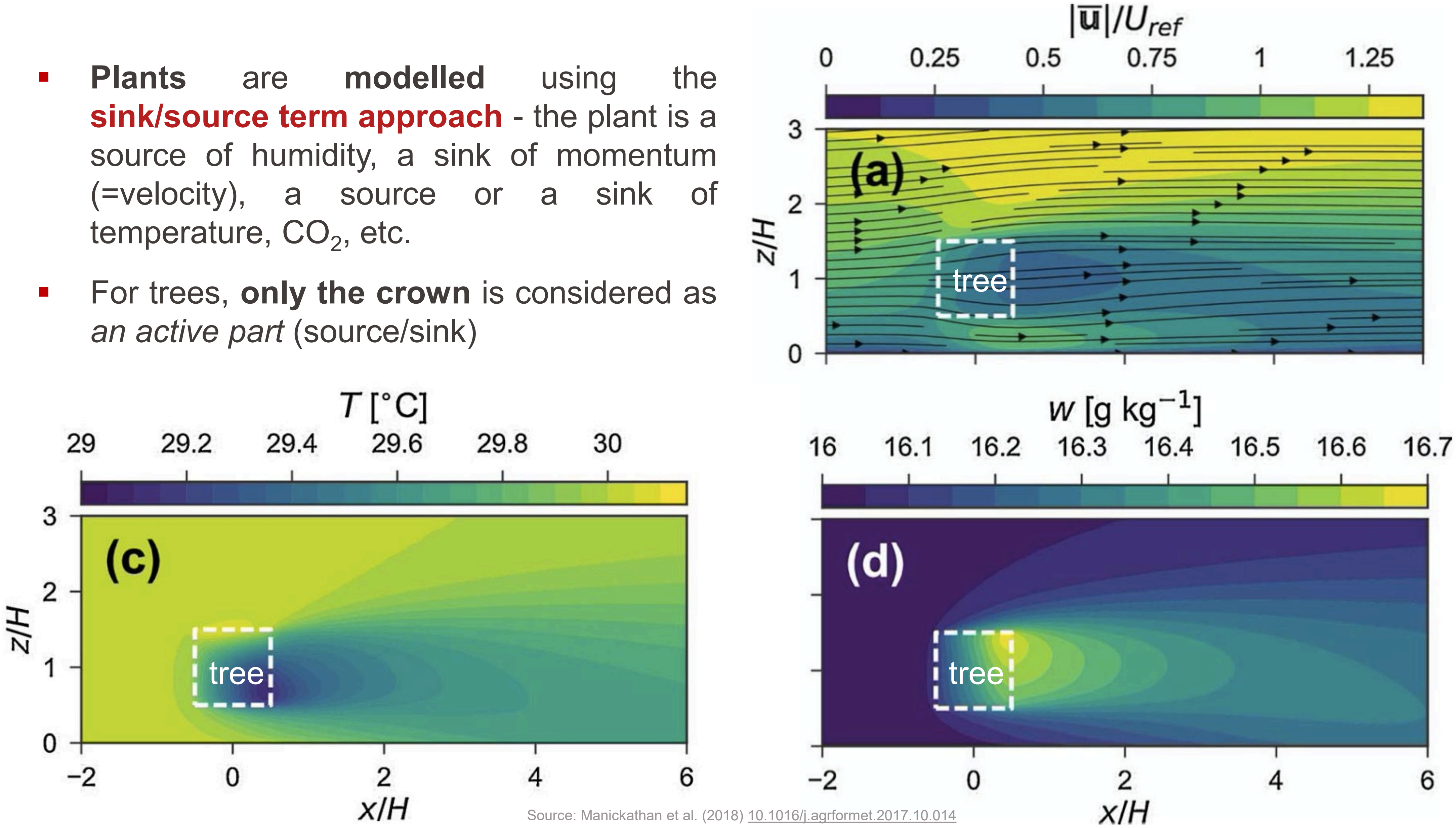




Source: Nobel, Physicochemical and environmental plant physiology, p. 419

Vegetation: Sink/Source Modelling Approach

- **Plants** are **modelled** using the **sink/source term approach** - the plant is a source of humidity, a sink of momentum (=velocity), a source or a sink of temperature, CO_2, etc.
- For trees, **only the crown** is considered as *an active part* (source/sink)



Source: Manickathan et al. (2018) 10.1016/j.agrformet.2017.10.014

Vegetation: Leaf Characteristics

- **Leaves area LA** (m^2): **area** of the **upper faces** of **leaves** within *a* vertical cylinder of $(z - h_0)$ height

(9-2) $$LA(z) = \int_z^{h_0} A(z)dz$$

$A(z)$ – foliage area density function over the height, h_0 (m) - height of the crown top

- **Leaf area index LAI** ($\frac{m^2}{m^2}$): **leaves area** per **unit projection area (GA)** on **the ground**

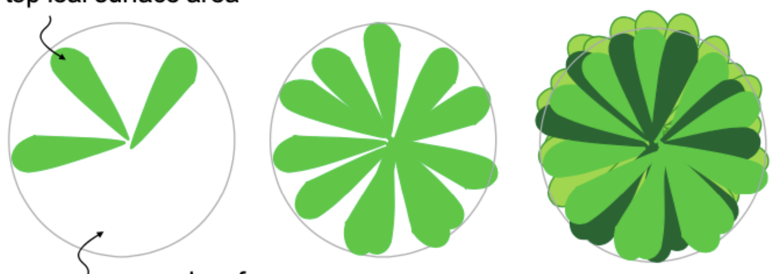
$$LAI(z) = \frac{LA(z)}{GA} \quad (9\text{-}3)$$

  - LAI varies with species, foliage density, and growth rate (age)
  - For barren land $LAI = 0\ \frac{m^2}{m^2}$, for dense forest $LAI \approx 8\,\frac{m^2}{m^2}$

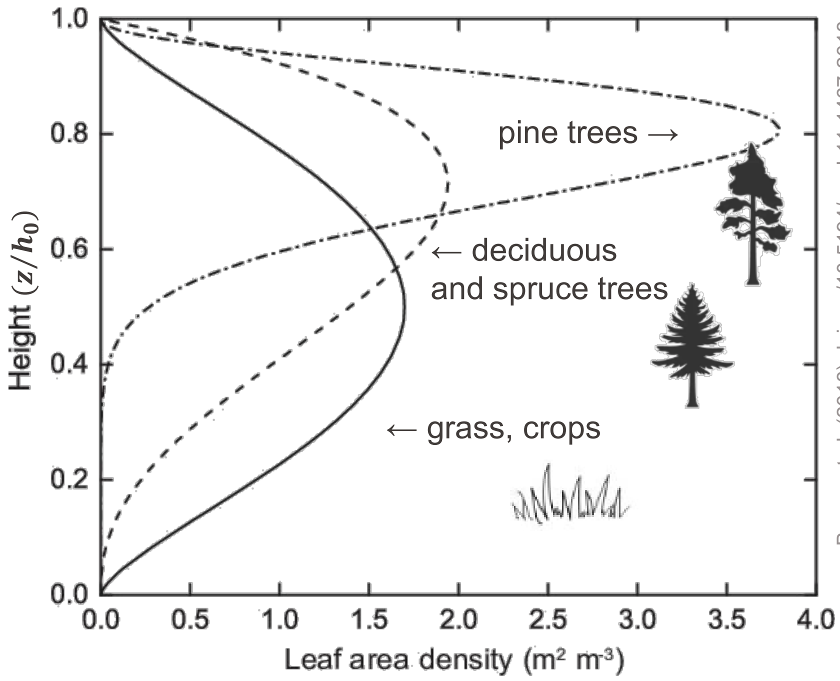
- **Leaf area density LAD** ($\frac{m^2}{m^3}$): **area** of ***upper faces*** of **leaves** $(1/2$ of the total leaf area) per **unit volume**

- **Plant area index PAI** ($\frac{m^2}{m^2}$): overall **area** of the **plant** *within a vertical cylinder* of *unit cross-section*, including both the leaf area index (LAI) and the woody-element area index (WAI)

$$PAI = LAI + WAI \quad (9\text{-}4)$$



Source: Medved, Building Physics, p. 68



Bonan et al. (2018) doi.org/10.5194/gmd-11-1467-2018

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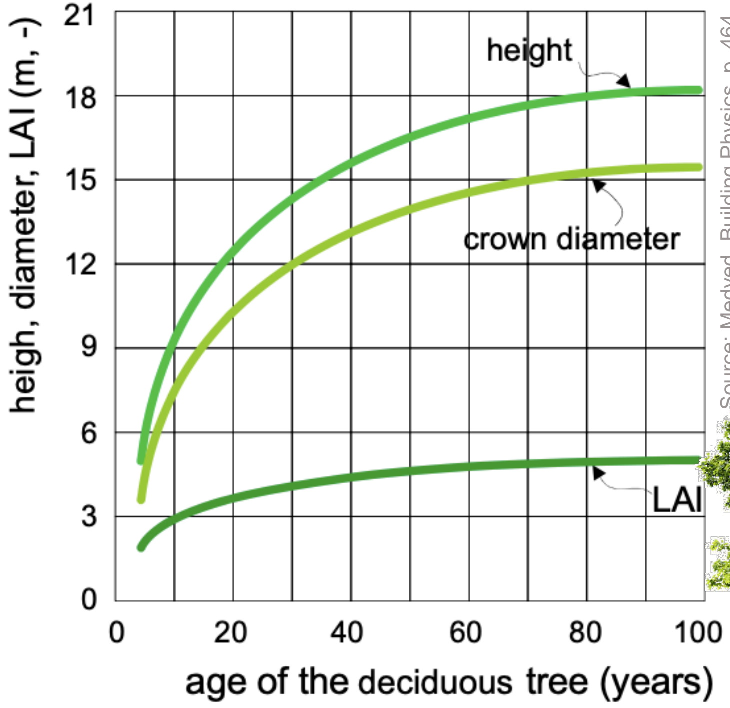
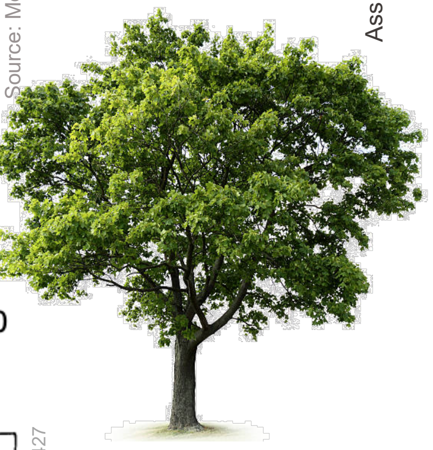
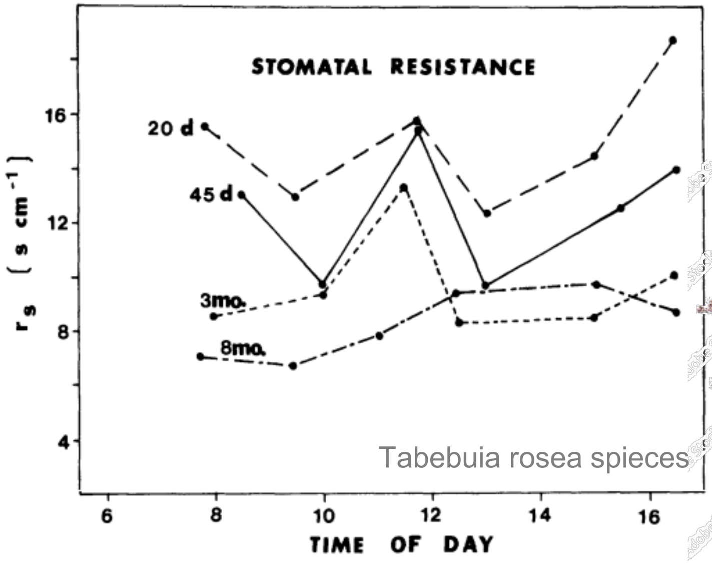
Vegetation: Characteristics

- **Vegetation properties** are **not constant**, they vary with:
  - **Season** (e.g., LAI of deciduous trees is zero during winter but not null outside of the winter season)
  - **Weather** (e.g., under strong solar irradiation, stomatal pores close themselves)
  - **Plant species** (e.g., the characteristic leaf size varies with plant species)
  - **Plant age** (e.g., young plants tend to have a higher stomatal resistance than more mature ones)
  - **Plant experience** (e.g., the growth of a plant growth depends on exterior factors)



Source: Medved, Building Physics, p. 464





doi.org/10.2307/2388427

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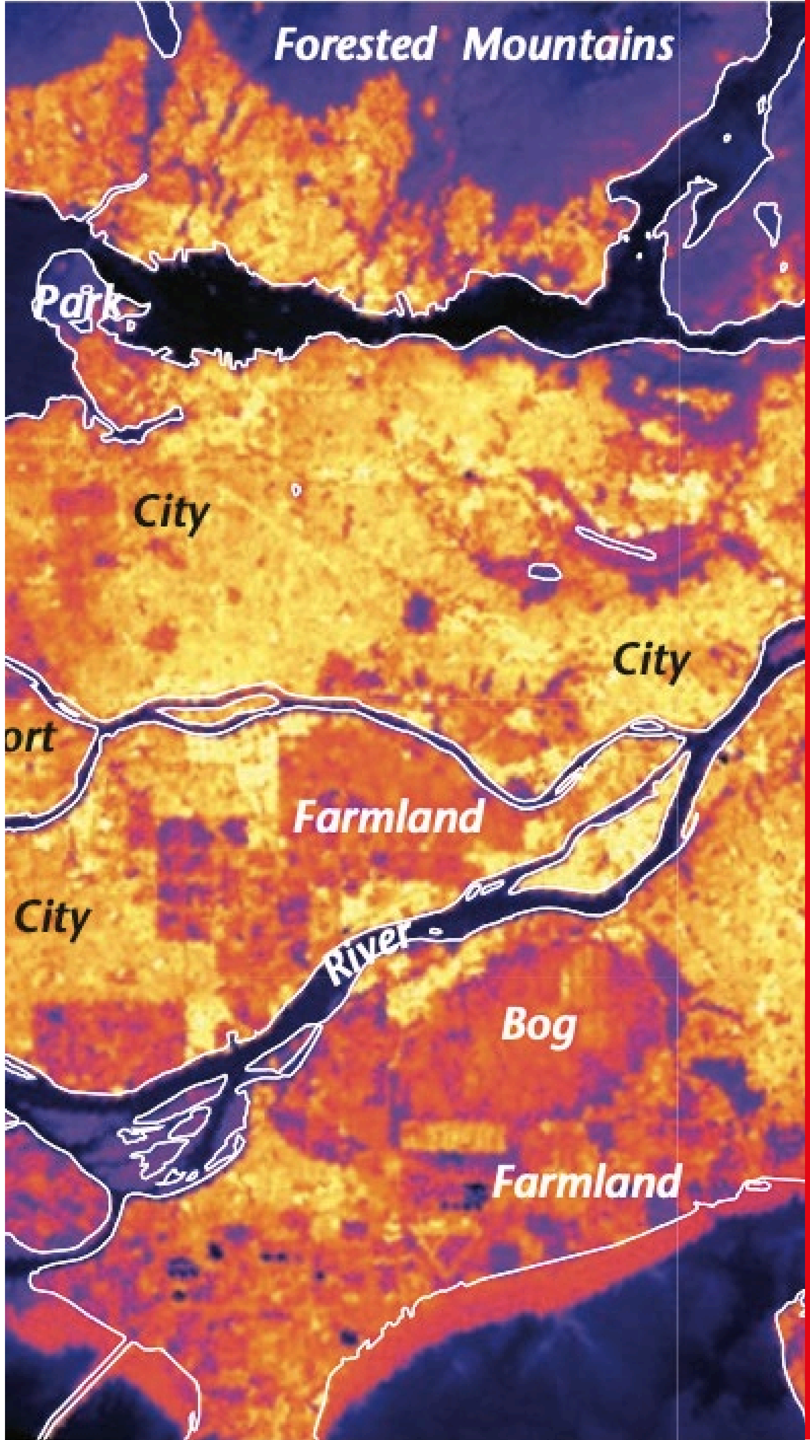

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I. Introduction
- Role of vegetation in urban areas
- UHI effect mitigation using vegetation

II. Characteristics of vegetation
- Leaves (their function, leaf area density)
- Aerodynamic characteristics
- Vegetation @ EPFL and Project 2

III. Energy balance
- Radiative properties, solar radiation
- Longwave radiation

IV. Evapotranspiration

V. Summary

Vegetation @ EPFL campus

Rsmin – minimal stomatal resistance

Species name	Number	LAI (m2/m2)	LAD (m2/m-3)	Rsmin (s/m)	Growth speed (m height/yr)	Max size (m height)
Tilia	41	5.30	0.95	348.18	0.47	16.76
Acer	31	5.50	0.50	511.95	0.30	20.57
Betula	15	3.70	0.97	313.63	0.61	18.29
Carpinus	15	2.85	3.69	464.23	0.30	10.80
Prunus	15	5.10	1.22	1078.89	0.38	18.29

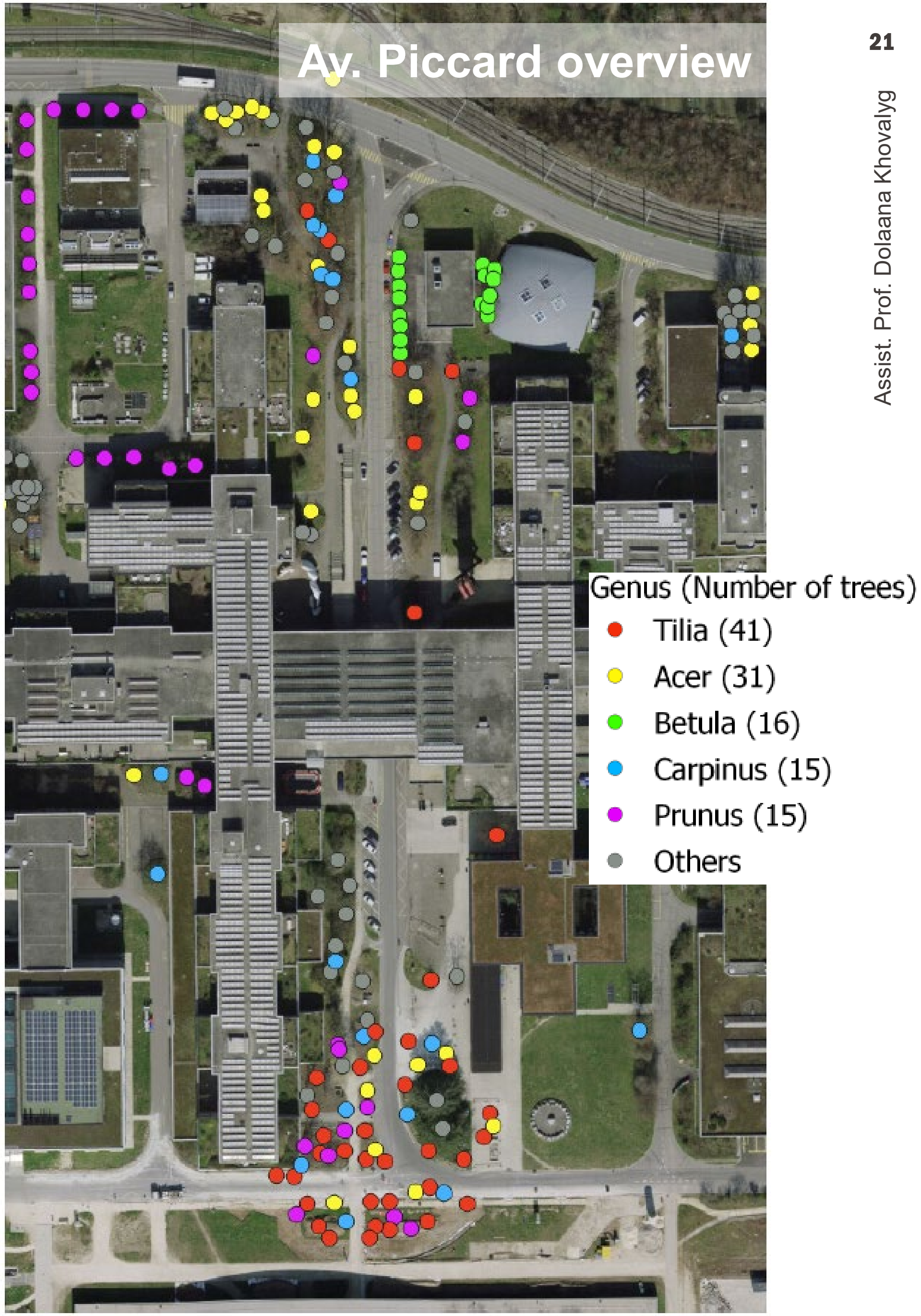
Tilia

Acer

Betula

Carpinus

Prunus



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Vegetation in Project 2

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Table 6: General Properties of Plants

Scenario / Plant Type	Height (m)	Diam. (m)	α	ϵ	τ	LAI	LAD
S2.3 Plant - *Funika*	0.3	n/a	0.20	0.97	0.30	1.5	0.15
S3.3 Grass - aver	0.25	n/a	0.20	0.97	0.30	2.0	0.3
S4.1 Hedges - dense	1.0	n/a	0.20	0.97	0.30	1.0	1.0
S4.2 Tree - *Betula*	6.0	7.0	0.18	0.96	0.30	4.0	0.8
S4.3 Tree - *Acer*	11.0	9.0	0.50	0.96	0.30	5.0	0.7

* α (Albedo), ϵ (Emissivity), τ (Transmittance), LAI (Leaf Area Index, m^2/m^2), LAD (Leaf Area Density, m^2/m^3).

Table 8: Detailed Biomechanical Properties of Tree Species

Scenario / Tree Species	Leaf Weight [g/m^2]	Root Diameter [m]	Root Depth [m]	Wood Density [kg/m^3]
S4.2 Tree - *Betula Pendula*	100.0	10.0	1.40	590.0
S4.3 Tree - *Acer Negundo*	100.0	10.0	2.00	590.0

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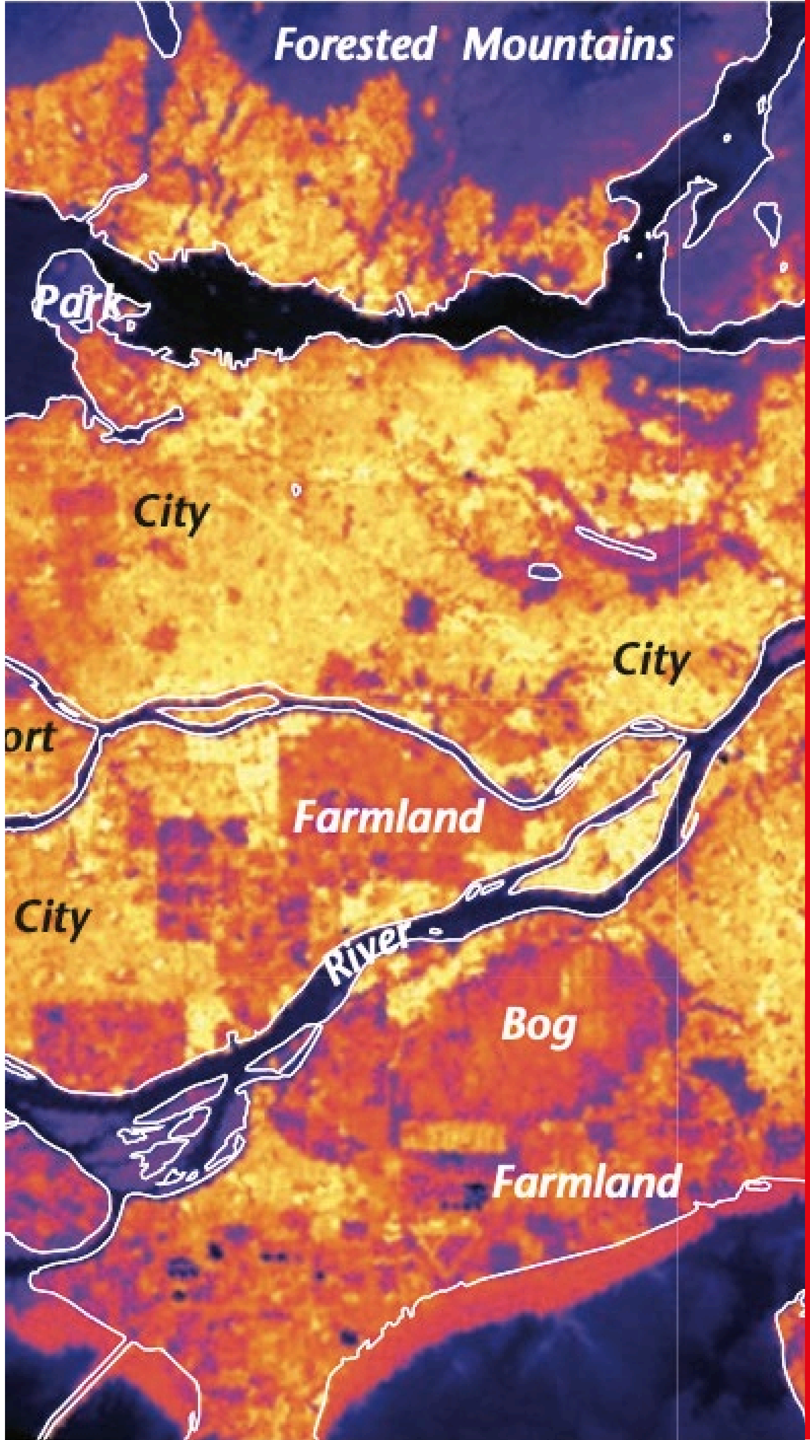

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II. Characteristics of vegetation
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III. **Energy balance**
- **Radiative properties, solar radiation**
- **Longwave radiation**

IV. Evapotranspiration

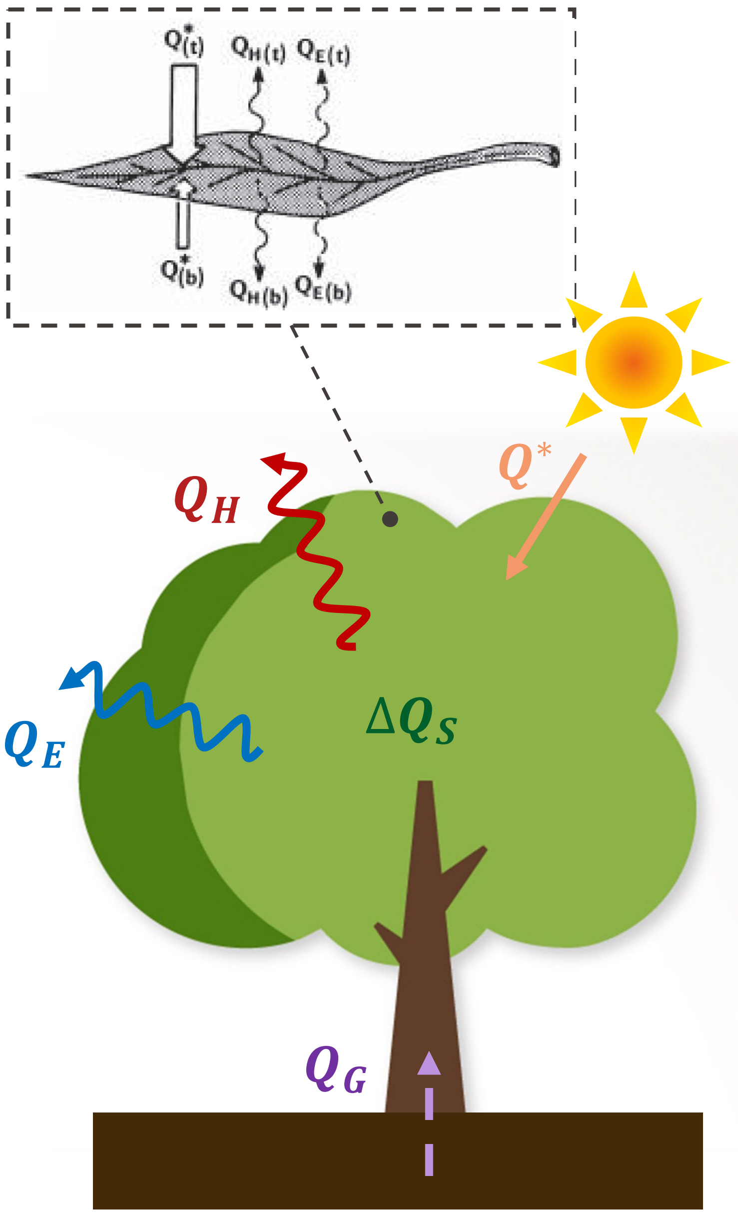
V. Summary

Vegetation - Environment: Energy Balance

- Vegetation interacts with the atmosphere, the Sun, the ground and other urban elements including buildings.
- The vegetation **(a plant canopy**) interaction with its environment is always *at balance*. It is the sum of **radiation budget**, **sensible heat**, **latent heat**, ground heat and stored heat.

$$Q^* = Q_H + Q_E + Q_G + \Delta Q_S \quad (1\text{-}3a)$$

Radiation budget · Sensible heat · Latent heat · Ground heat · Stored heat



- ○ **Vegetation latent heat** Q_E is *controlled* by the **water supply** which mainly comes from the ground
- ○ **Energy storage** ΔQ_S = *physical* heat storage + *biochemical* heat storage
- ○ All heat fluxes follow a **diurnal variation** (increase after sunrise and decrease with the lack of direct solar radiation at night)
- ○ **Incident solar heat flux** is **the main driver** of *all heat fluxes*.

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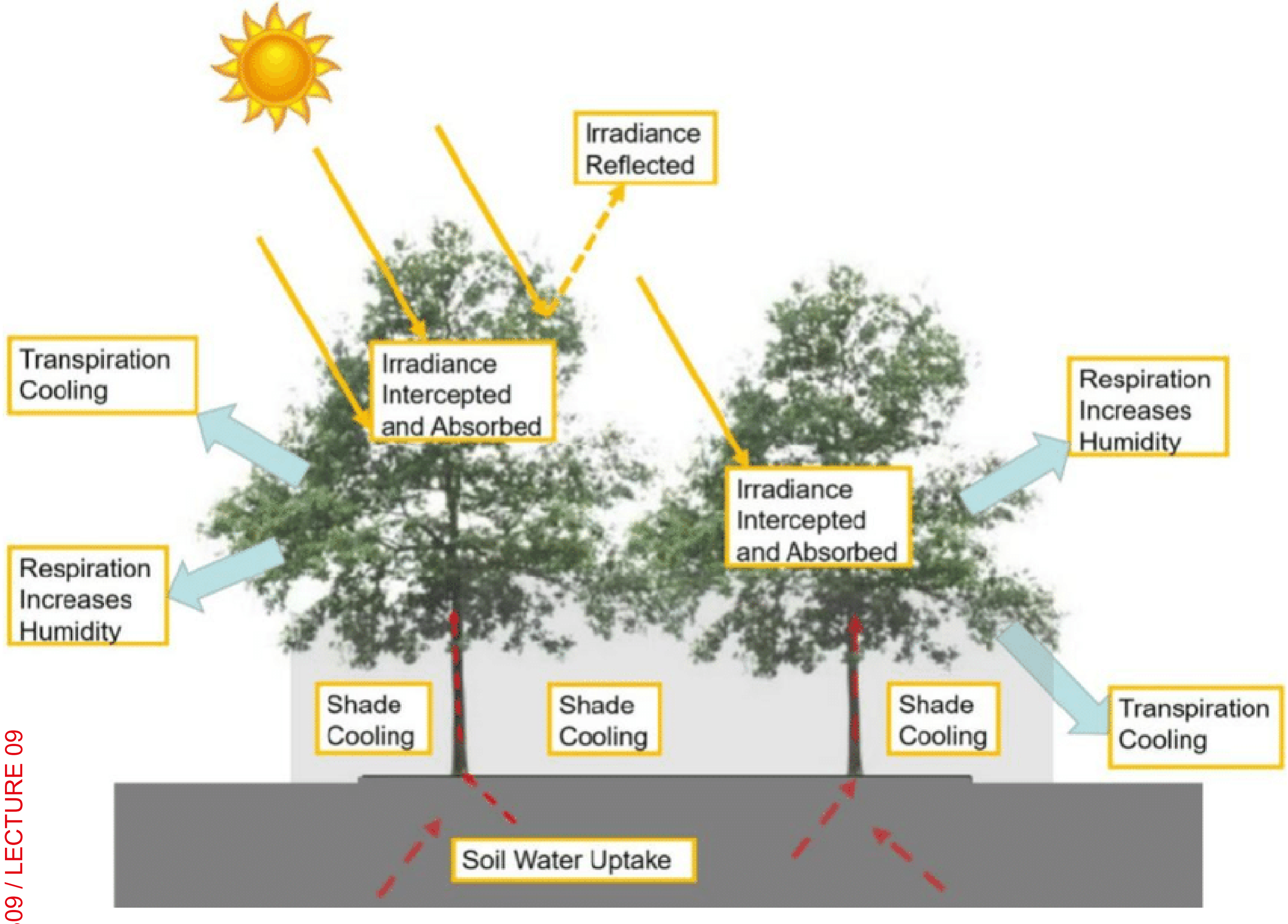
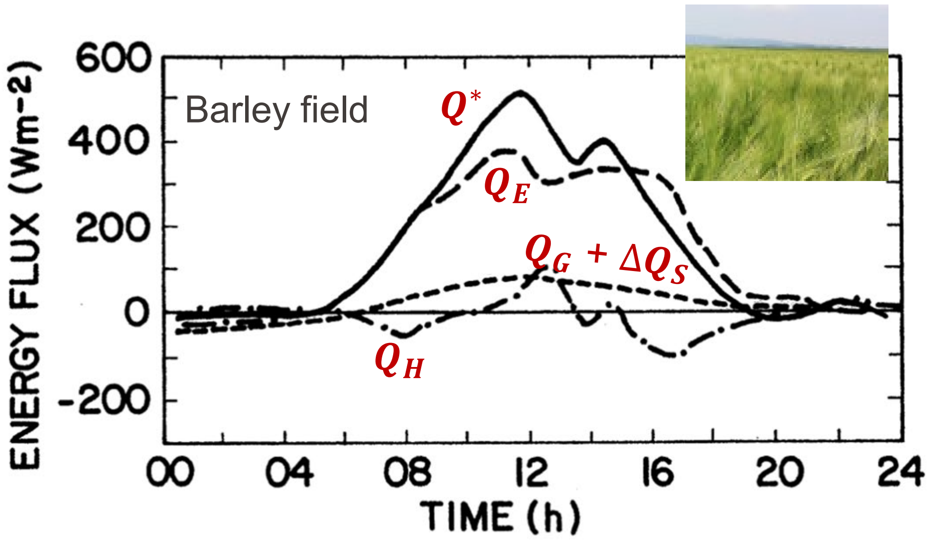
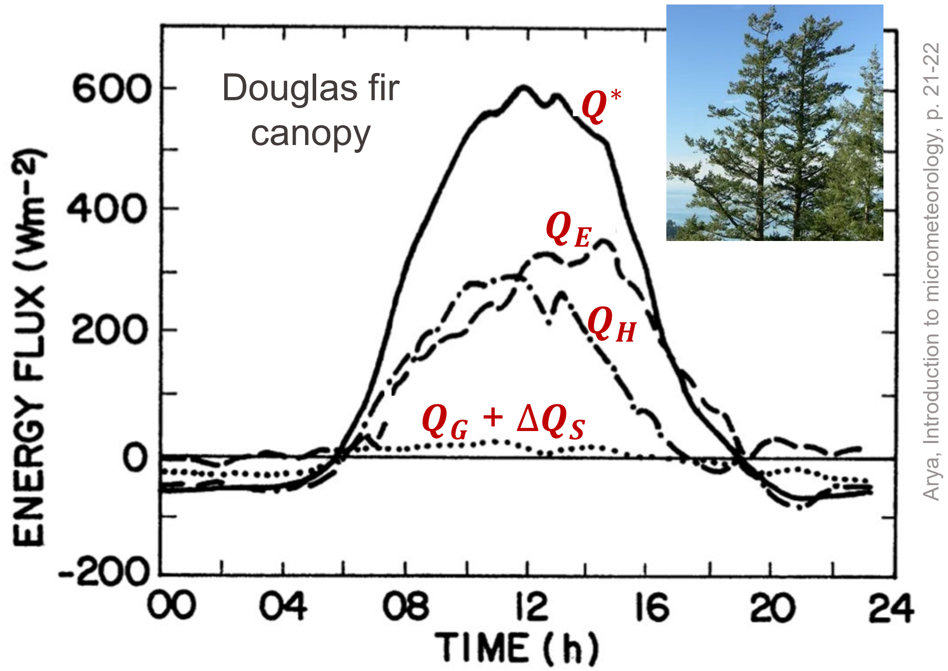
Vegetation - Environment: Energy Balance



Source: Zhang et al/ (2019) 10.3934/environsci.2019.6.417





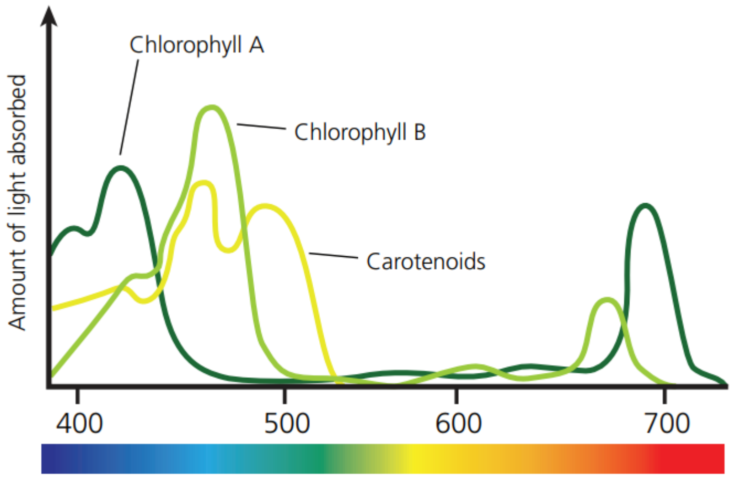
Arya, Introduction to micrometeorology, p. 21-22

Vegetation: Radiative Properties

- Green vegetation **reflects shortwave solar** radiation ***more effectively*** than *man-made structures.*

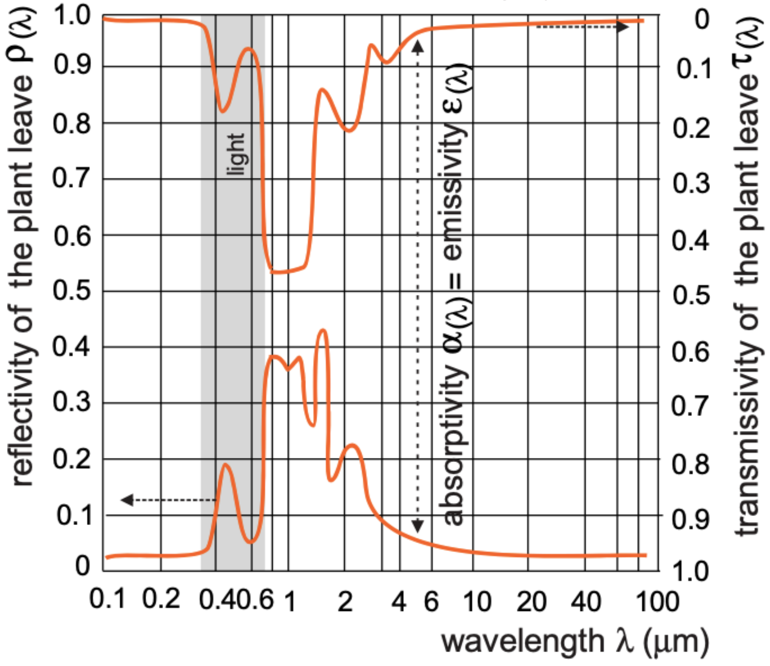
- Leaves **absorb** only **solar radiation** in the wavelengths *involved in photosynthesis* (**~0.4-0.5** *and* **~0.6-0.7 *μm***), green light (**~ 0.5-0.6 *μm***) is reflected.

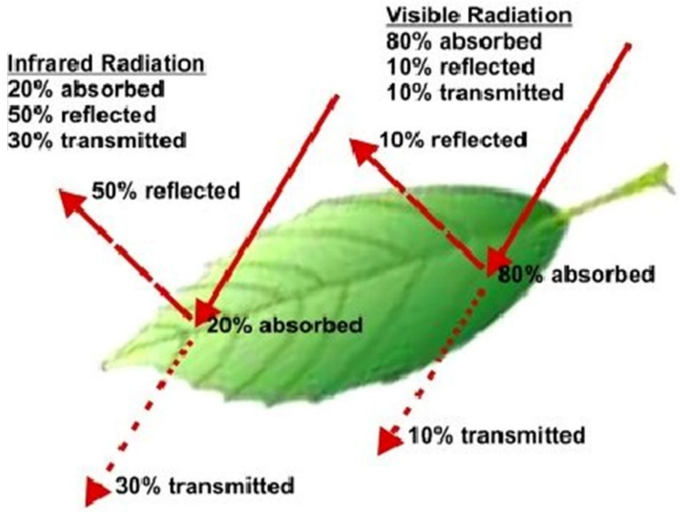
- **High reflectivity** of the *thermal part of solar radiation* (**0.78 < λ < 3 μm**) and **high emissivity** and **absorptivity** of thermal radiation (**λ > 3 μm**) lead to **reduced overheating of the leaves** and **performing them as micro sunshades.**



Source: websource

Source: Medved, Building Physics, p. 68



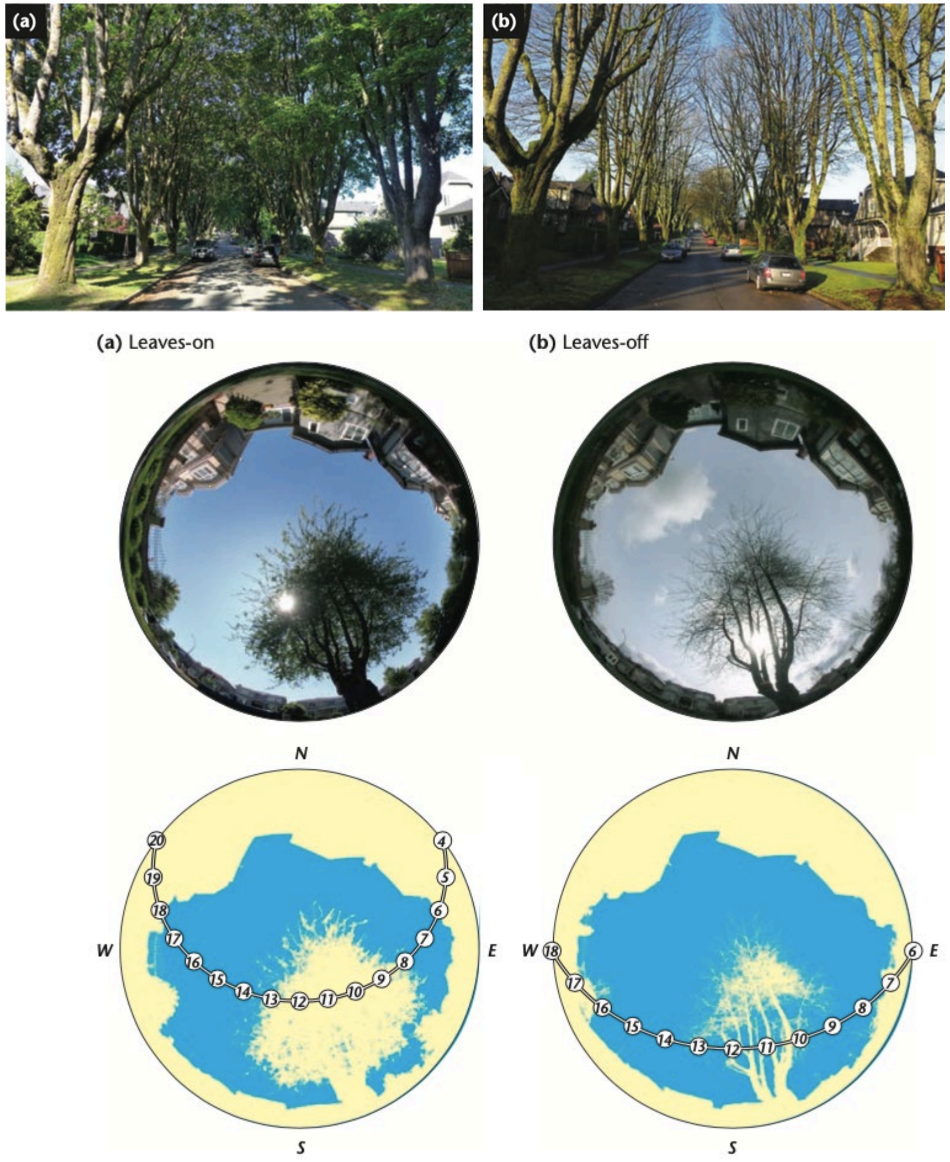


Source: Brown and Gillespie (1995) Microclimate Landscape Design

Vegetation: Shading effect

- **Shading** keeps the **air** and **surface temperature cooler** by *intercepting* solar radiation, *preventing energy absorption* by urban surfaces and re-radiation of heat to the upper urban elements.
- **Shading area** created by vegetation depends on the **size of leaves**, **crown area**, and the **leaf area index:**
  - **Trees** and **shrubs** create large shaded areas
- **A canopy foliage** *attenuates* the solar radiative flux:
  - **Deciduous species**: transmit **10-30%** in summer (**50-80%** in winter), ideal for cold winters and hot summers.
  - **Coniferous species**: transmit **10-30%** year round.
- **A canopy foliage** changes *its spectral composition:*
  - **Selective absorption** of visible light by leaves reduces the *photosynthetic value* of the solar radiation as it penetrates through the depth of the canopy
  - **Sunflecks** vs. **shaded areas**: the spectrum is similar to that of incident total radiation in *sunflecks*, while NIR (near-infrared) dominated in *shaded areas*.

Source: Oke, Urban Climates, p. 435-436



(a) Leaves-on (b) Leaves-off

Vegetation: Solar Radiation

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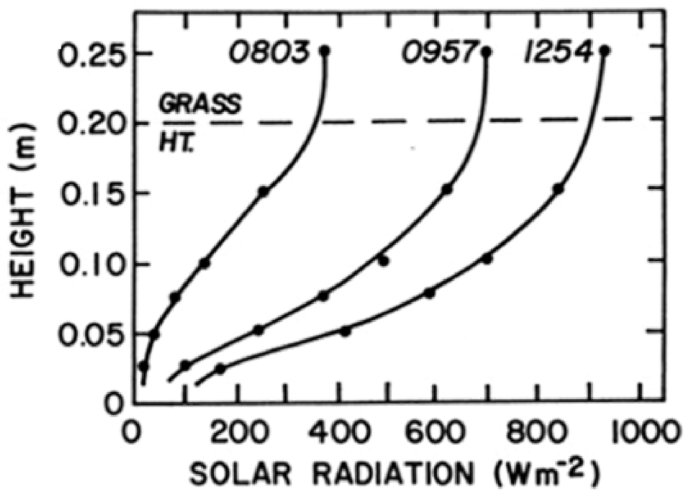
- The ***transmission*** of **incoming shortwave radiation** *into a plant canopy* shows approx. **exponential decay** *with* **depth of penetration** depending on:
  - **Leaf density** (leaf area index LAI)
  - **Solar altitude angle** (reflectivity ↑ for normal incoming radiation)
- **The Beer-Bouguer law for shortwave radiation**:

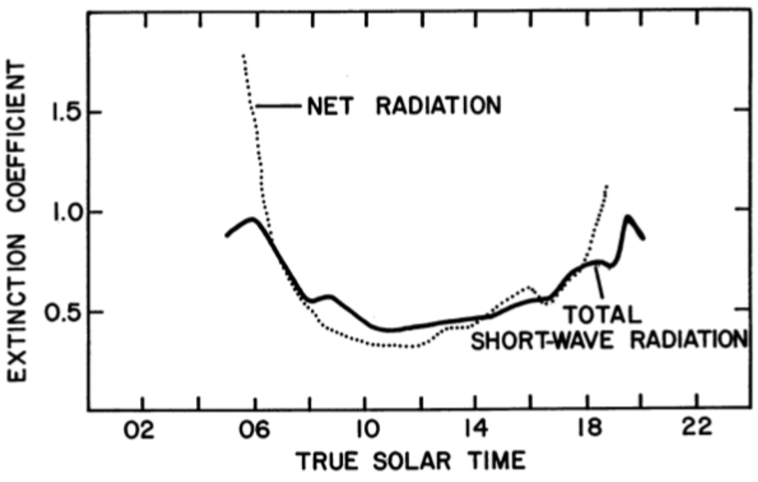
$$S(z) = S(h_o) \cdot e^{-\alpha \cdot LAI(z)} \quad (9\text{-}5)$$

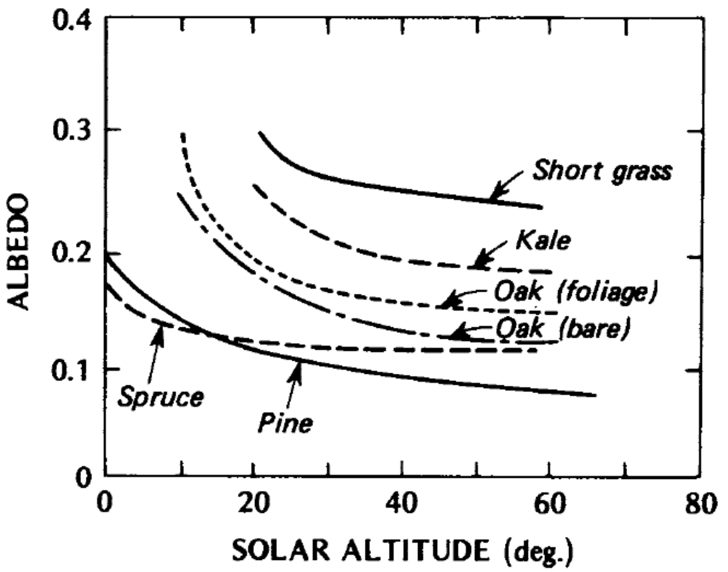
α (-) - *extinction coefficient (varies diurnally), indicates how strongly a plant attenuates the intensity of light as it travels through it;*
h_o(m) - *top of the canopy (overall height),* LAI (m^2/m^2) – *leaf area index*

Incoming solar radiation (S) of native grass (Canada), a clear summer day



Diurnal variation of S and Q* extinction coefficients for native grass (Canada)



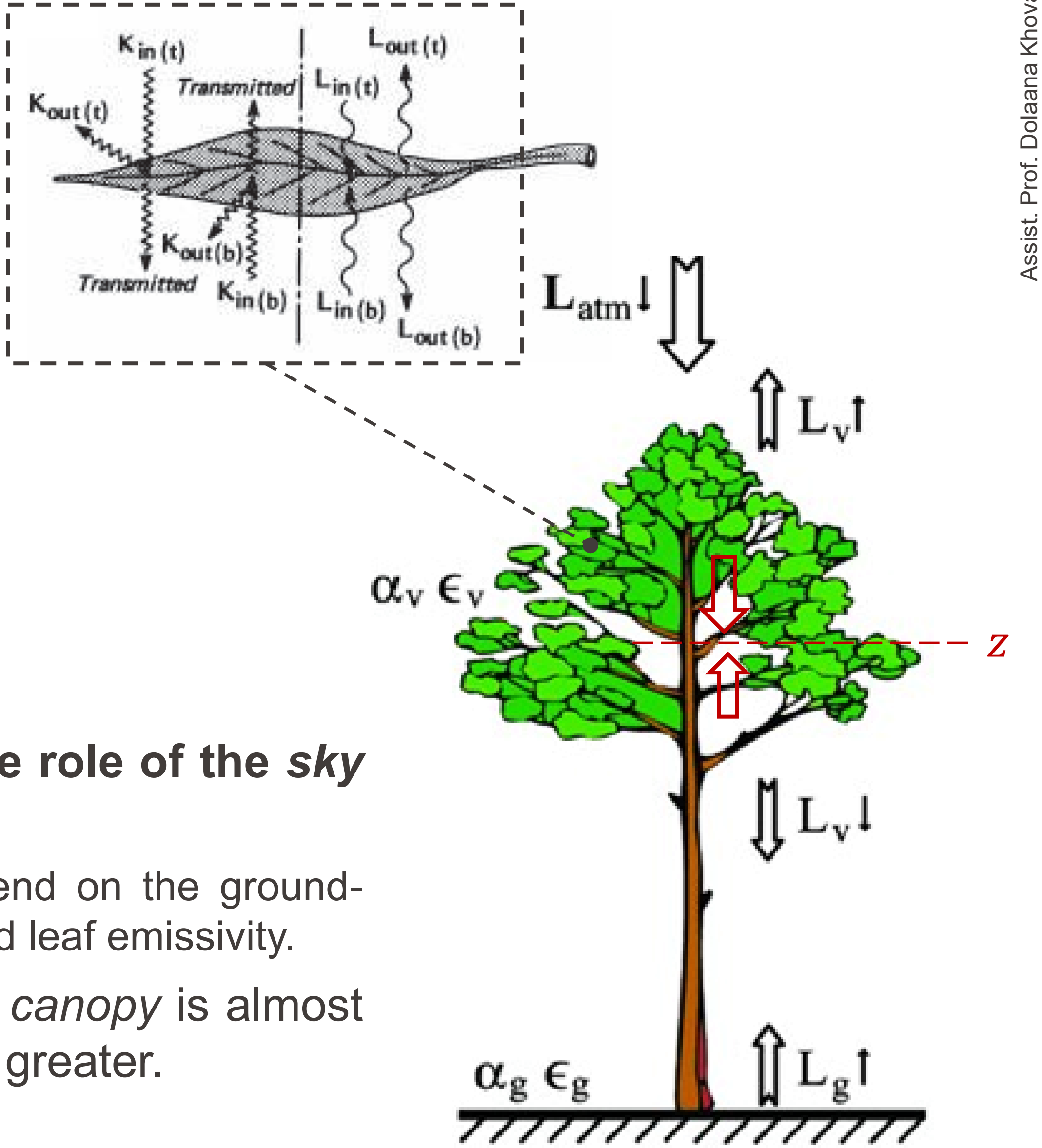


- **Shortwave reflectivity** (**albedo**) of a plant canopy is *lower* than the value for its *individual leaves* because of the reflection dependence from the penetration, radiation trapping, and mutual shading within the canopy volume.
- Most leaves have $a = 0.3$, but the albedo of plants is a function of **their height**, **age**, and **solar altitude**.

Source: Arya, Introduction to microcmeteorology, p. 374

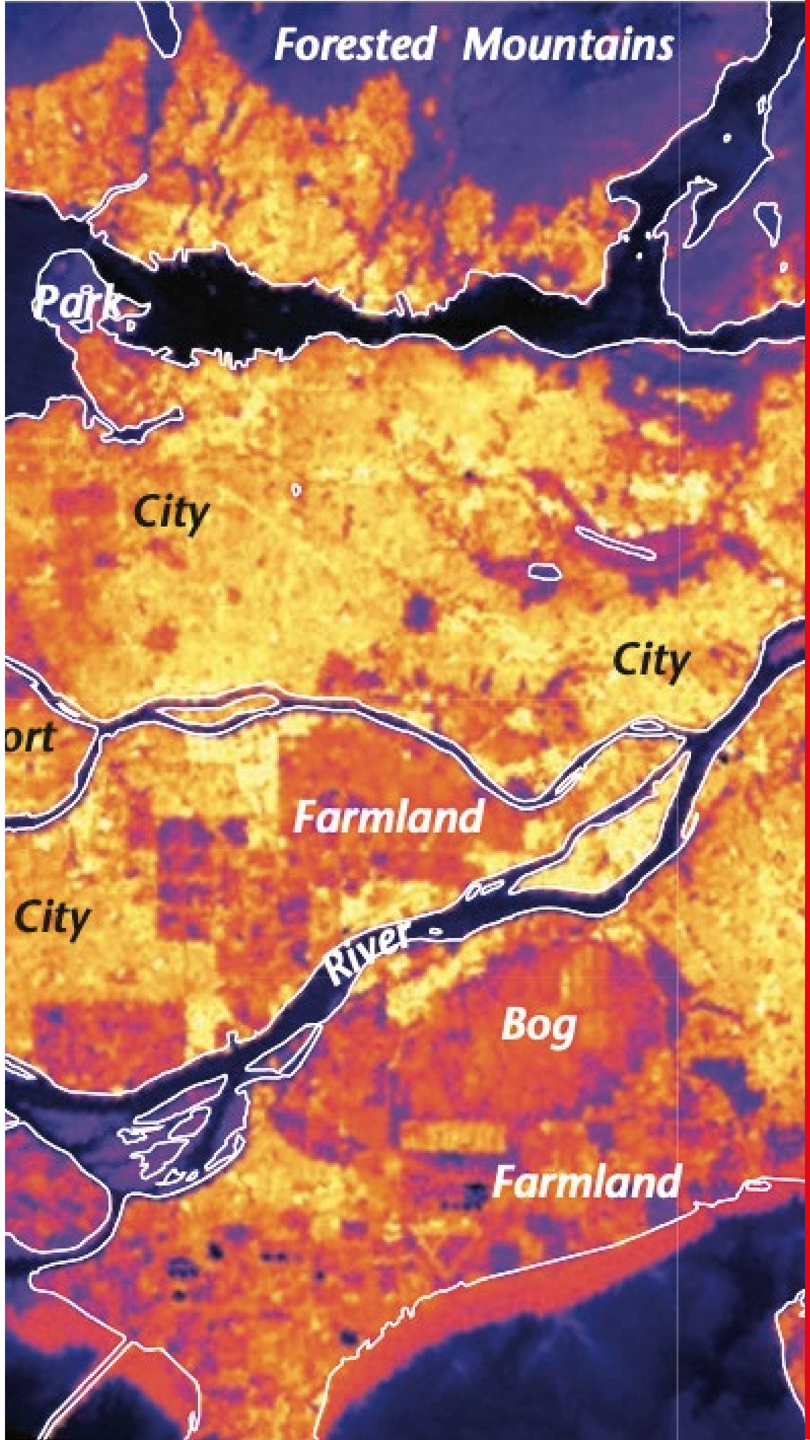
Vegetation: Longwave Radiation

- **The net longwave radiation** *at any height* within a plant canopy has **4 components**:
  1. From the **atmosphere** penetrated trough the *upper layer of the canopy* without interception
  2. From ***the upper leaves*** and ***other canopy elements***
  3. From ***the lower canopy elements***
  4. Part of ***outgoing radiation from the ground*** not intercepted by lower canopy elements.



- For the **bottom** of **tall** and **dense tree canopy**, **the role of the *sky* becomes insignificant**.
  - The longwave radiation exchange is primarily depend on the ground-surface temperature, foliage temperature, ground and leaf emissivity.
- The net longwave radiation L^* at the *top* of a *plant canopy* is almost always *negative* ($L^* < 0$) as outgoing LW radiation is greater.

Source: Ivanov et al. (2008) 10.1029/2006WR005588


Forested Mountains
Park
City
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Farmland
City
River
Bog
Farmland

CONTENT:

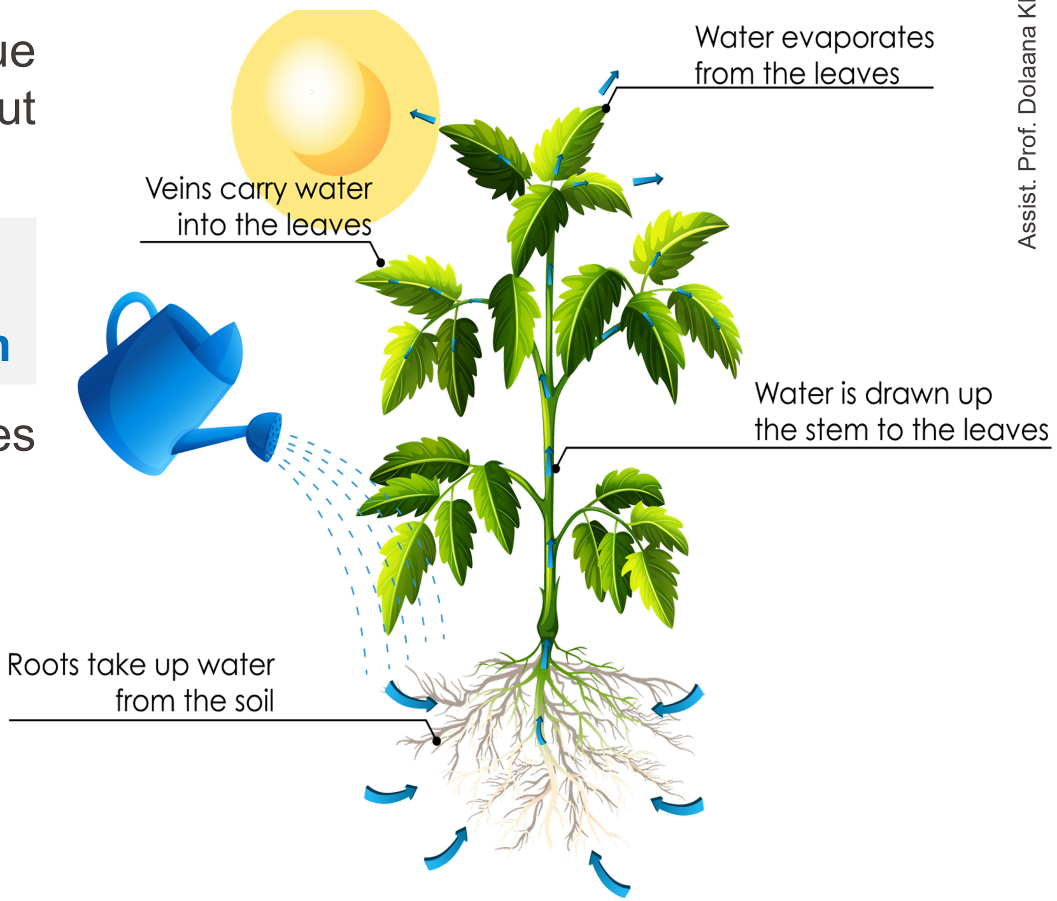
Vegetation: Evapotranspiration

- **Latent heat exchange** with vegetation happens due to **evaporation** or **condensation** *at the surface* but also due to **transpiration** from *the plant leaves*.

Evapotranspiration =

evaporation of soil humidity + **plant transpiration**

- **Transpiration** is *water loss* through plant's pores (stomata). Transpiration depends on:
  1. Water availability
  2. Plant type
  3. Atmospheric conditions



- **Drivers of evapotranspiration:**
  - **Stomata opening** for photosynthesis
  - **Moisture deficit** (the drier the adjacent air, the more the transpiration).
  - **Wind speed** (determines aerodynamic resistance)
  - **Incoming radiation.** The more radiation, the less transpiration.

Vegetation: Latent Heat Flux and Evaporation

- **Latent heat flux density Q_E (W/m^2) for plants:**

$$Q_E = L_v \cdot ET \quad (1\text{-}6b)$$

$$Q_E = L_v \cdot ET_0 \cdot LAI \quad (9\text{-}6)$$

L_v (J/kg) – latent heat of vaporization
ET $[mm/(m^2 \cdot h)]$ - amount of water that evaporates from 1 m^2 of green area per hour
ET_0 $[mm/(m^2 \cdot h)]$ - reference amount of evaporated water
LAI $[m^2/m^2]$ – leaf area index

- **The reference amount** of **evaporated water** ET_0 in $[mm/(m^2 \cdot h)]$ is determined for:
  - 1 m^2 of hypothetical meadow with *a well-watered grass* height of 12 cm
  - Aerodynamic resistance $r_a = 208/U_2\ s/m$
  - Surface resistance $r_s = 70\ s/m$
  - Surface albedo $a = 0.23$

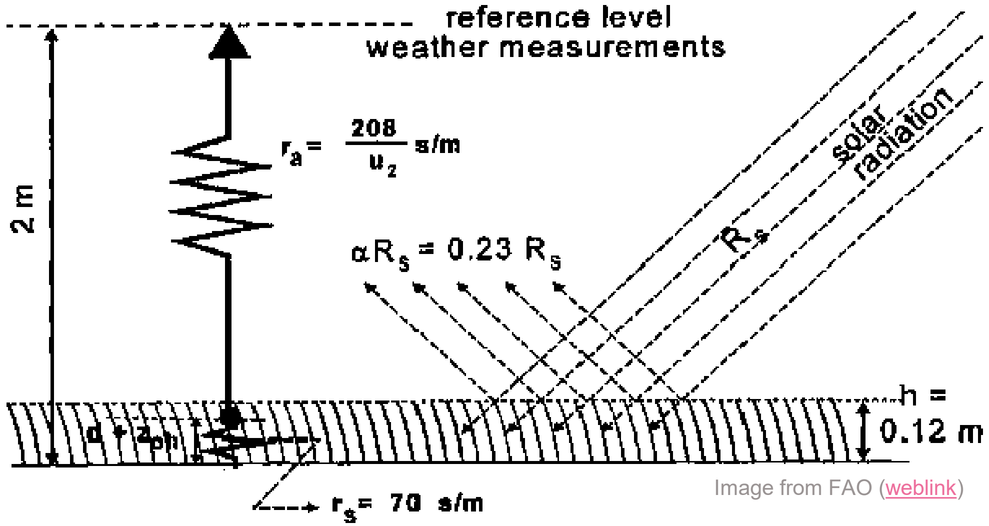


Image from FAO (weblink)

- Empirical expression for ET_0 $[mm/(m^2 \cdot h)]$:

Source: Medved, Building Physics, p. 68

$$ET_0 = 0.0299 + 0.005 \cdot t_a - 0.0022 \cdot \varphi_a + 0.00058 \cdot \alpha_s \cdot S \quad (9\text{-}7)$$

t_a (°C) - outdoor air temperature, φ_a (-) - relative humidity of outdoor air,
S (W/m^2) - incident solar radiation, α_s (-) – solar absorptivity of the plant

For plants with sufficient watering in dry moderate climate:

- $ET_0 = 3 - 6\ \frac{mm}{m^2 h}$ at $20°C$
- $ET_0 = 6 - 10\ \frac{mm}{m^2 h}$ at $30°C$

Vegetation: Evapotranspiration under Water Stress

- Three major categories of plants with different **transpiration mechanisms**:
  - **C3 & C4 photosynesis**: **stomata remain opened during day**, significant water volume transpired. Plants in cold and humid climates.
  - **CAM photosynesis: stomata stay closed during day**, water loss avoided, don't contribute to evapotranspiration. Plants in hot and dry climates. (e.g., cactus)

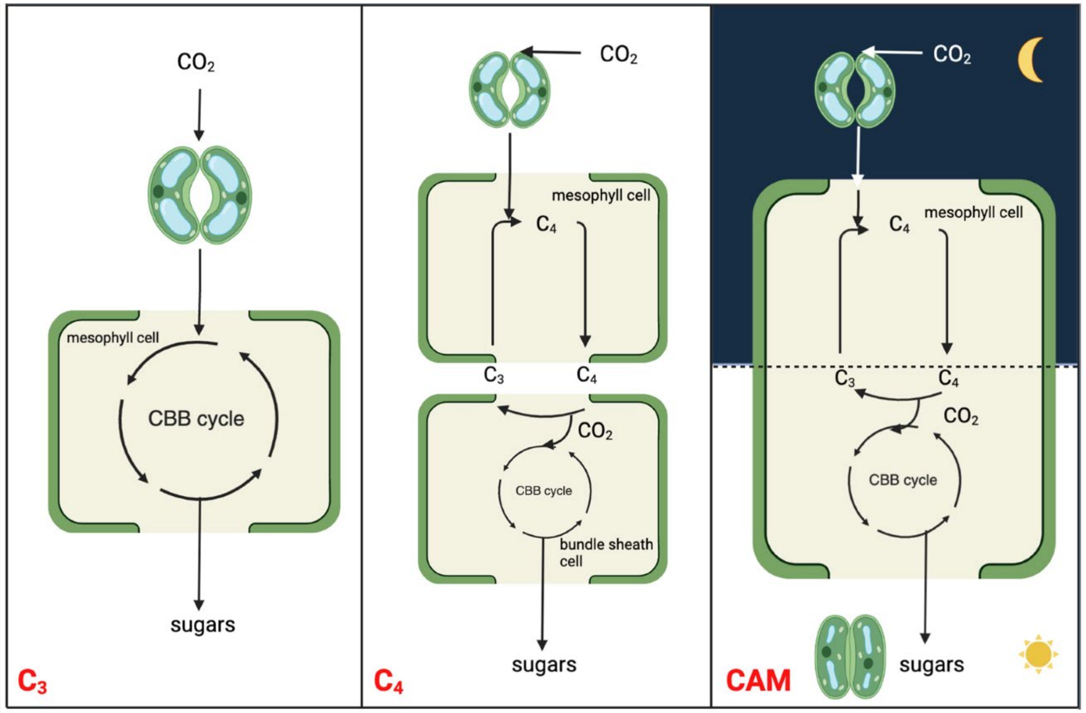
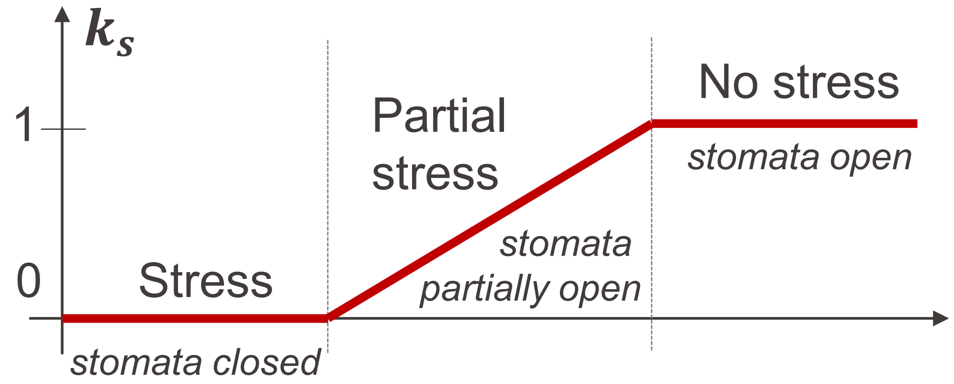


Image from weblink

- **Water stress** *affects* the *amount of water transpiration during the day*, thus, their evaporative cooling effect.
- The stress coefficient k_s needs to be considered in determining the latent heat flux of plants in stress.

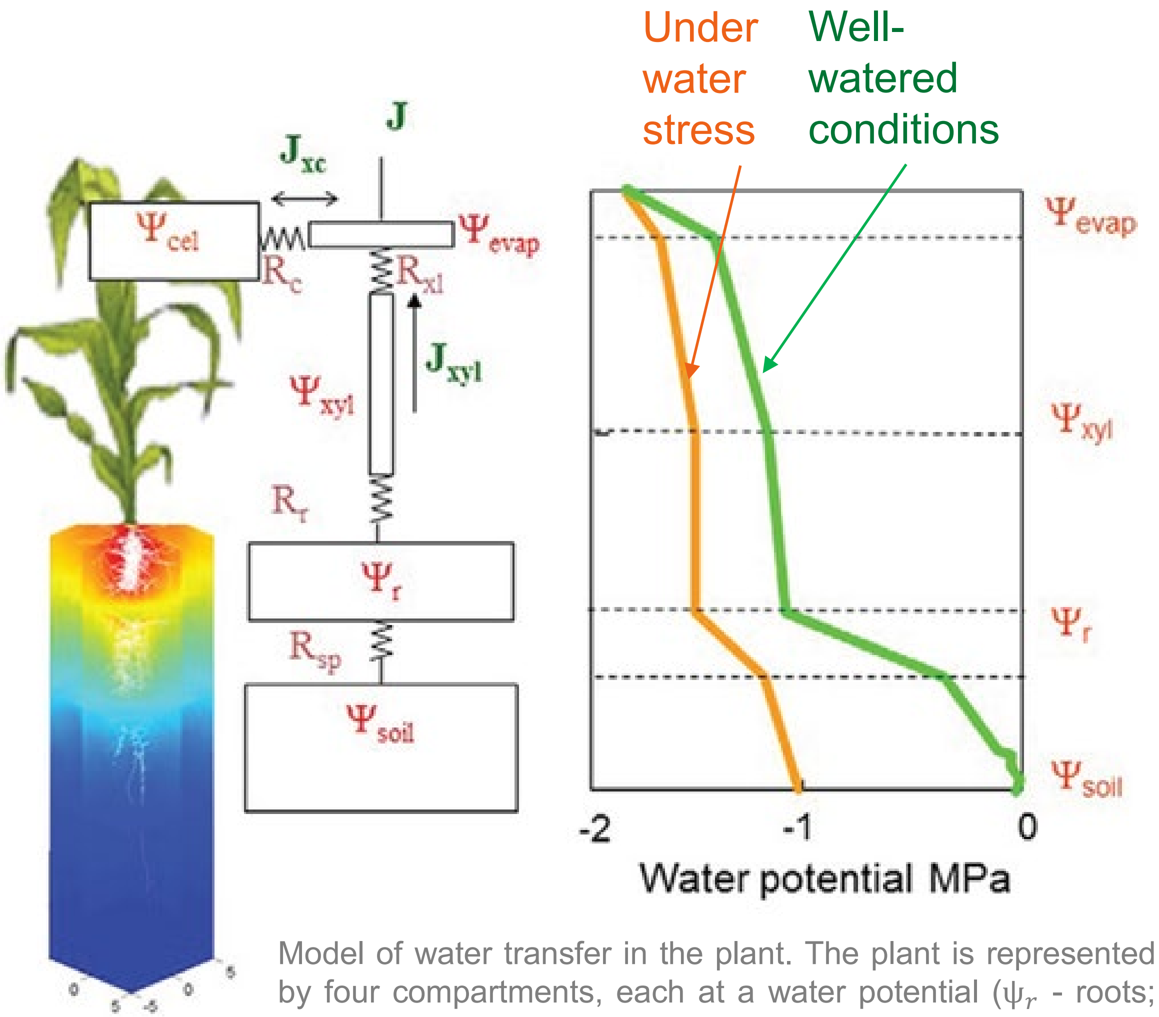
$$Q_E = k_s \cdot L_v \cdot ET_0 \cdot LAI \quad (9\text{-}7)$$



Evapotranspiration: Root water uptake

Assist. Prof. Dolaana Khovalyg

- Usually, all **water entering a plant** transported from *the soil* via *roots*. It is *conducted up to the leaves*, mainly in the **xylem (vascular tissue)**.
- **Water transport** faces *resistances* in each *element* and at *each interface* between all elements: soil, root, xylem, leaves, air.
  - For **a *young root*** of diameter 1 mm, uptake of water ~ 10 to 50 *ml* per day per meter of root length.
  - Influx of water enhanced by **root hairs** (often about $12\ \mu m$ in diameter, up to $1\ mm$ long with frequency from 0.5 to 50 per mm).
  - **Older roots** lack root hairs, the water flux can be only 1% to 5% compared to the one of young roots.



Model of water transfer in the plant. The plant is represented by four compartments, each at a water potential (ψ_r - roots; ψ_{xyl},- xylem; ψ_{evap}, - sites of evaporation; ψ_{cel} - leaf cells), separated by resistances Rsp between the soil and roots, Rr between the soil–root interface and the xylem, and Rxl from the xylem to the evaporation sites.

Source: Tardieu et al. (2017) doi.org/10.2136/vzj2017.05.0107

Evapotranspiration: Root water uptake

Assist. Prof. Dolaana Khovalyg

- **Water volume flux density J_V** $(m^3/(m^2 \cdot s))$ **supplied to the plant** (per Darcy's law in 1D):

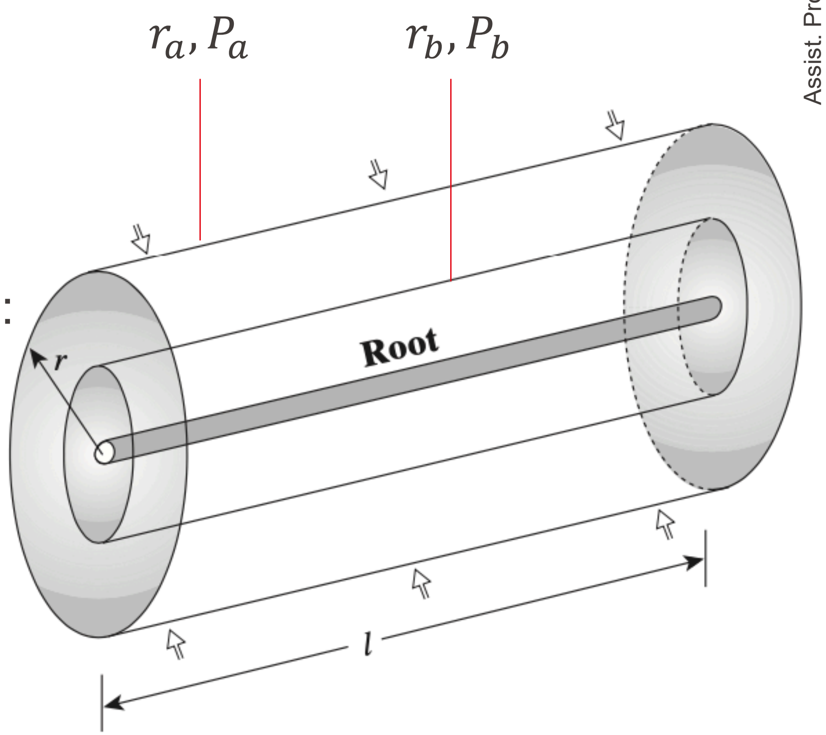
$$J_V = -L_{soil} \cdot \frac{\partial P_{soil}}{\partial x} \quad (9\text{-}9)$$

L_{soil} $[m^2/(Pa \cdot s)]$ - soil hydraulic conductivity coefficient,
$\partial P_{soil}/\partial x$ (Pa/m) - hydrostatic pressure gradient in soil

- **Water volume flux density J_V** in cylindrical coordinates ($r_a > r_b$):

$$J_V = -\frac{1}{r_b} \cdot \frac{L_{soil} \cdot (P_a - P_b)}{\ln(r_a/r_b)} \quad (9\text{-}9a)$$

P_a (Pa) - hydraulic pressure at $(r_a - r_b)$ distance away from the root, P_b (Pa) - hydraulic pressure at the root surface, r_b (m) – root radius, $(r_a - r_b)$ (m) – distance away from the root where P_a is known.



- **The volumetric mass flux of water ϕ** (m^3/s) through the cylindric roots:

$$\phi = J_V \cdot A = J_V \cdot 2\pi \cdot r_b \cdot l \quad (9\text{-}10)$$

l (m) – length of the root system under consideration

Source: Nobel, Physicochemical and Environmental plant physiology, p.521

Evapotranspiration: Root water uptake

Example: Consider a plant with an average diameter of a plant root of **0.5 mm**. The cumulative length of the plant root system is 600 m.

- The soil hydraulic conductivity coefficient is $\boldsymbol{L_{soil} = 10^{-15}\ \mathrm{m^2/(Pa \cdot s)}}$.
- At the root surface, the hydrostatic pressure is $\mathbf{P_b = -0.2\ MPa}$.
- At a distance **1 cm** away from the roots, the hydrostatic pressure drops to $\mathbf{P_a = -0.4\ MPa}$.

Question: What is the volume flux density of water of the global plant root system for: (a) one second, (b) for one day?

1. Volume flux density of the root (in cylindrical coordinates) per square mater of the root:

(9-9a) $$J_V = -\frac{1}{r_b} \cdot \frac{L_{soil} \cdot (P_a - P_b)}{\ln\left(\frac{r_a}{r_b}\right)} = -\frac{1}{5 \times 10^{-4}} \frac{10^{-15}(-0.4 + 0.2)}{\ln\left[\frac{0.5 + 10}{0.5}\right]} = 1.3 \cdot 10^{-7} \frac{m^3}{m^2 \cdot s} = \mathbf{0.13} \frac{cm^3}{m^2 \cdot s}$$

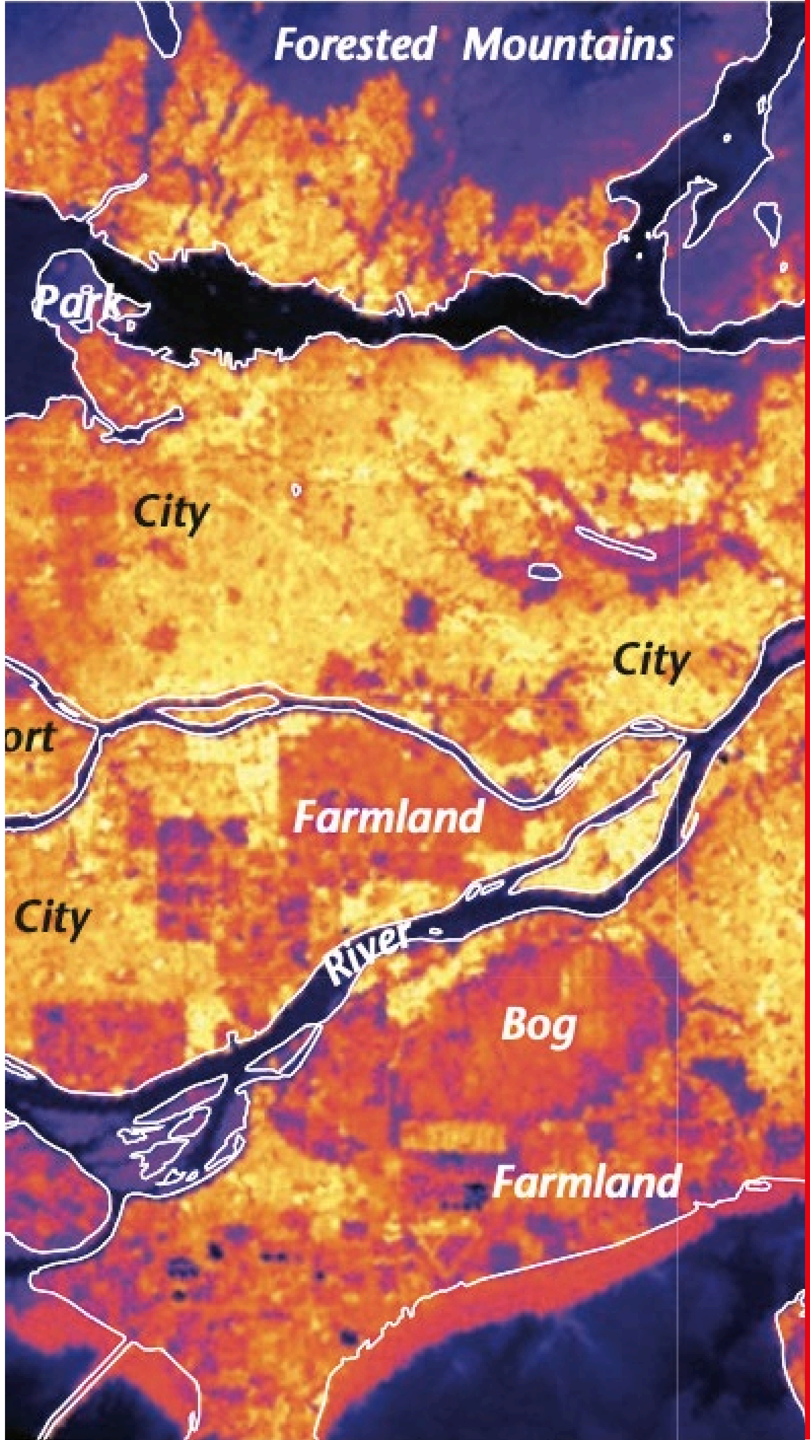
$\mathbf{0.13\ cm^3}$ of water is absorbed **every second** for **every square meter** of the plant root

2. Volume flux density of water of the global plant root system for: (a) one second, (b) for one day:

(9-10) $$\phi = J_V \cdot 2\pi \cdot r_b \cdot l = 1.3 \cdot 10^{-7} \cdot 2\pi \cdot 5 \times 10^{-4} \cdot 600 = 2.45 \times 10^{-7}\ m^3/s$$

Over a day, $\phi_{day} = \boldsymbol{\phi} \cdot 24 \cdot 3600 = 0.022\ m^3 \Rightarrow$

Under the given underground conditions, the plant absorbs **22 liters of water** every day by its roots.


Forested Mountains
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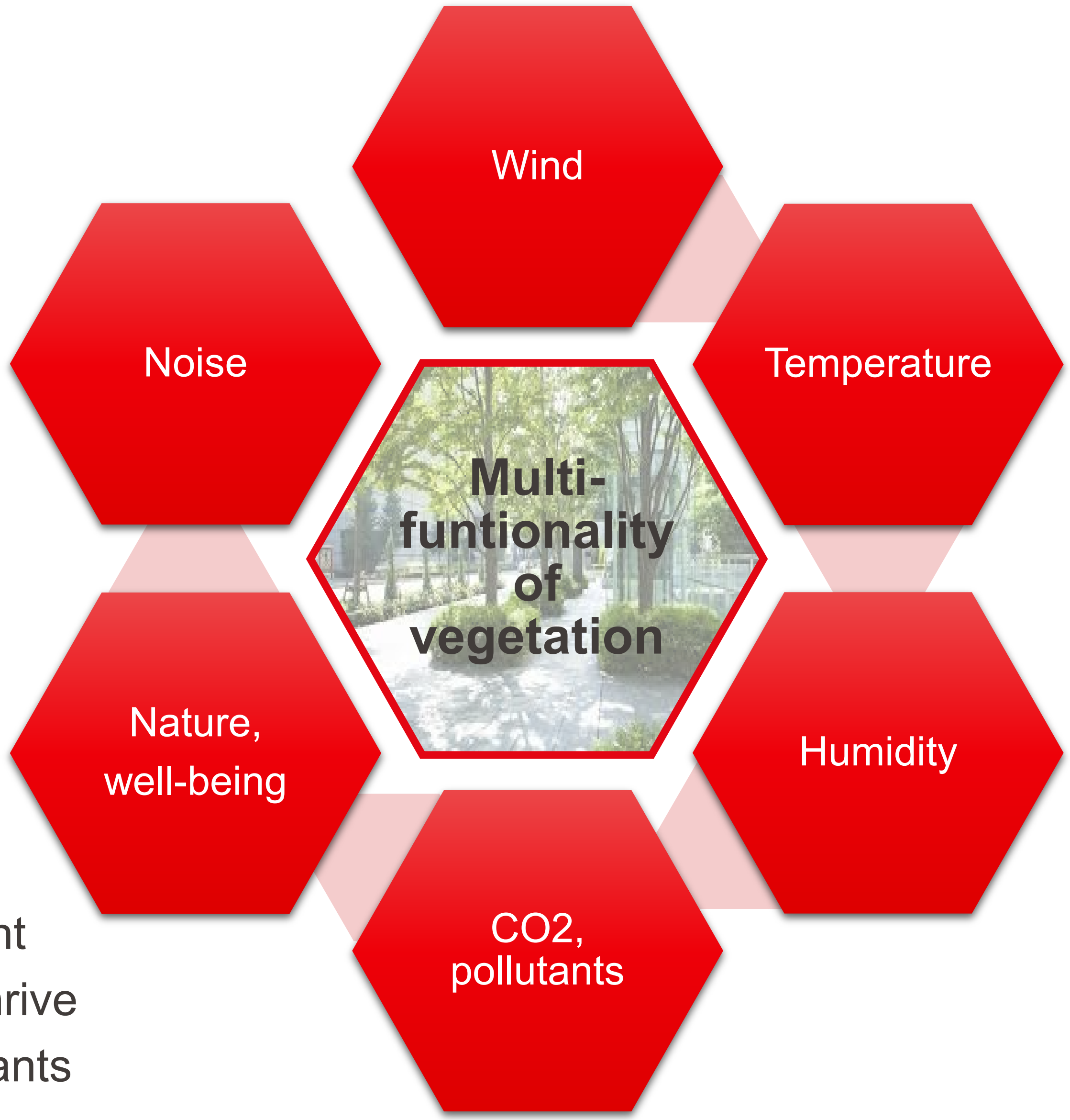
River
Bog
Farmland

CONTENT:

Vegetation - Environment: Summary

- **Advantages:**
  1. Regulation of microclimate and UHI
  2. Absorb CO_2 and other pollutants
  3. Increase water retention
  4. Provide recreation and well being
  5. Reduction of noise
  6. Production of oxygen
  7. Support biodiversity
  8. Protect soil from erosion

- **Disadvantages:**
  1. Inconstancy (seasonality)
  2. Need of maintenance (water supply)
  3. Many not suited for the urban environment
  4. Lack of space and proper conditions to thrive
  5. Emit and promote deposition of air pollutants



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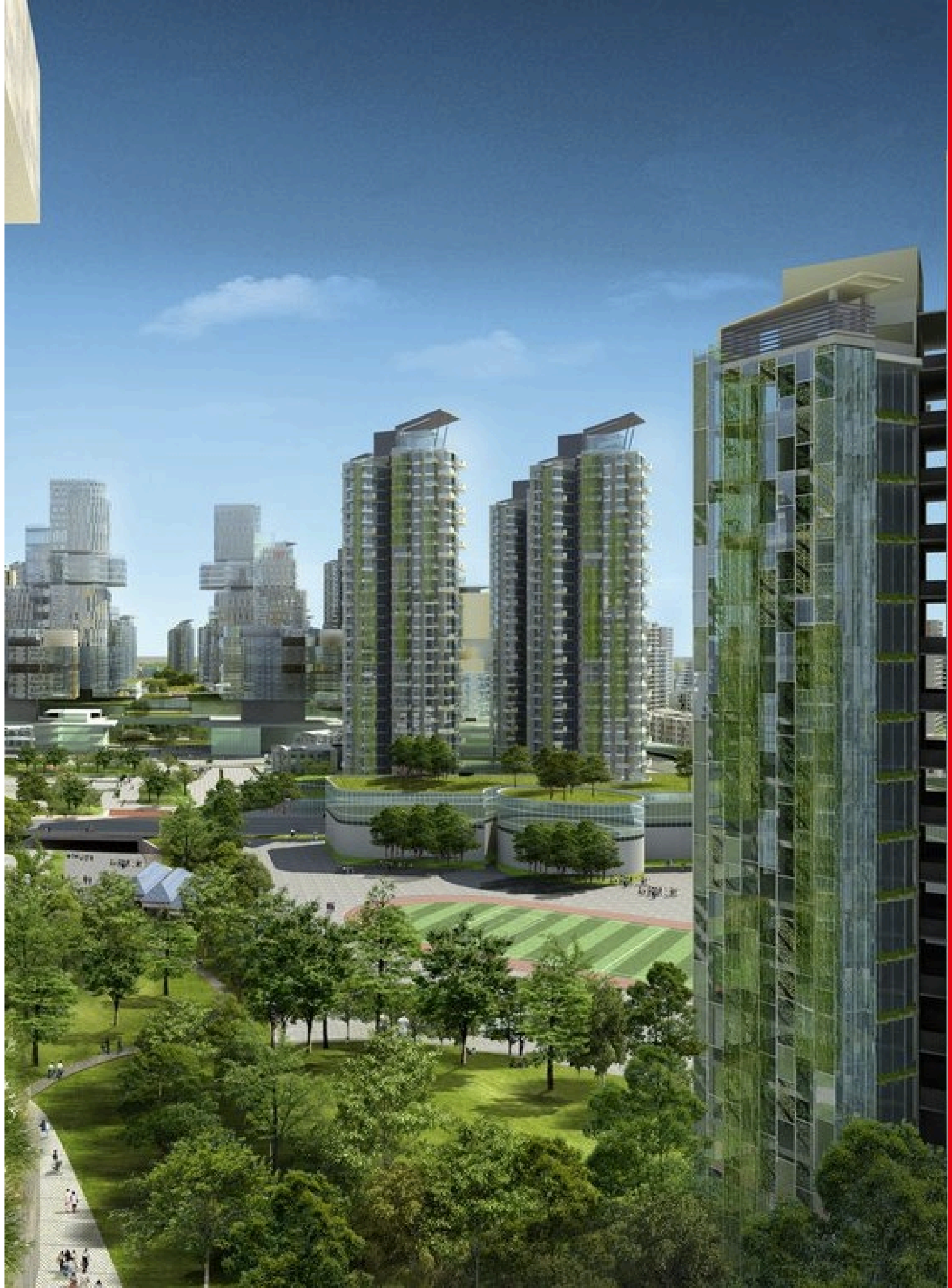

Thank you for your attention!

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