Green Roofs and Green Facades

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GREEN HOUSE BEYOND
LIVING WALL
BALCONIES
GREEN WALL &
GREEN ROOF
PHOTOVOLTAICS
ACCESS BETWEEN LEVELS
AND GREEN ROOF
MECHANICAL ROOM
DBL. SKIN FACADE
GREEN ROOF
GREEN ROOF
MECHANICAL, STORAGE,
OVERFLOW
LABORATORIES
CIRCULATION & GARDEN COMMONS
COURTYARD
(STREAM, TREES, LIVING LABORATORY)
OFFICES &
ADMIN.
CAFE
AUDITORIUM & EXHIBIT SPACE
ENTRY / ECO. MACHINE

VEGETATION

Importance of **urban sustainability**

- Increased urbanization
- Global warming
- Urban Heat Island (UHI) effect
  - Global warming manifestation in urban environments
- Stratospheric ozone depletion
  - Affects concentrated populations
- (Local) air pollution
  - Vehicles, building heating
- Noise pollution
- Decline in biodiversity

Sustainable/nature-based solutions to mitigate these issues

- Energy efficient buildings
- Use of renewable energy sources
- Urban green spaces
  - Expansion of green infrastructure
  - Creation of new urban green
- Air (and water) pollution mitigation techniques

These approaches help maintain a balance between biotic and abiotic ecosystem components

Urbanization increases demand for

- Buildings
- Space
    - Urban and rural lands
- Water
- Energy

Exploitation of **natural heat sinks** for excessive heat dissipation

- Ground
- Sky
- Water

Rooftops in urban areas

- Unused impervious surfaces (primarily)!

Green Roof (GR) and **Green Facade** (GF) technologies

- Technical
- Widely documented
- Nature-based solution

GR technologies can

- Improve sustainability in the built environment
- Increase building energy efficiency

Green technologies in urban areas

- GRs
  - Related terms
    - **Vegetated roofs**
    - **Planted roofs**
- GFs
  - Related terms
    - **Living walls**
    - **Vertical gardens**

GR (eco-friendly or vegetated roofing) economic and environmental benefits

- **Enhanced energy efficiency** through natural insulation and decreased reliance on heating and cooling systems
  - Substantial energy savings
- **Prolonged roof lifespan** through protection from UV rays and extreme temperatures, extended lifespan of roof membrane
  - Reduced need for repairs or replacements

GR (eco-friendly or vegetated roofing) economic and environmental benefits (continued)

- **Effective stormwater management** through absorption and retaining of rainwater
  - Reduced burden on stormwater management systems
  - Stormwater infrastructure maintenance cost savings
- **Enhanced air quality** through filtering airborne pollutants, generating oxygen (during the day)
  - Fostering a healthier environment even indoors
  - Potential reduction of healthcare costs (for building occupants)

GR (eco-friendly or vegetated roofing) economic and environmental benefits (continued)

- **Increased property value** due to higher resale or rental prices
  - Contribute to increased income and profits for building owners
- **Tax incentives and refunds** through financial incentives or rebates (offered by local authorities and organizations) for the installation of GRs
  - Helps offset installation costs

GR (eco-friendly or vegetated roofing) economic and environmental benefits (continued)

- **Aesthetic improvement** through the creation of an aesthetically appealing environment
  - Potentially attracting more customers, elevating the reputation of a building
- **Regulatory compliance**, as in certain regions GRs can help meet regulatory requirements for sustainability and environmental standards
  - Averting possible fines and penalties

GR (eco-friendly or vegetated roofing) economic and environmental benefits (continued)

- **Mitigation of the Urban Heat Island** by absorbing and reflecting heat, creating a more comfortable atmosphere in the vicinity of the building
  - Potential reduction of cooling costs
- **Noise reduction** as GRs can function as a sound insulator, reducing noise pollution within the building and enhancing the work or living environment
  - Can boost productivity and tenant satisfaction

Further **benefits** of GRs

- Psychological
- Physiological

GRs can transform

- An aesthetically indifferent space like a rooftop
    - Into a viable, multi-functional and sustainable area
        - Using soil, vegetation, and plants

More on **energy benefits** of GRs

- Energy conservation potential
  - Reduction of cooling and heating load
    - Building characteristics
    - Heat transfer processes
    - Climate type
    - System configuration parameters
      - Plant canopy characteristics, e.g. Leaf Area Index (LAI)
        - Shading
        - Evapotranspiration
        - Heat fluxes

More on **air quality benefits** of GRs

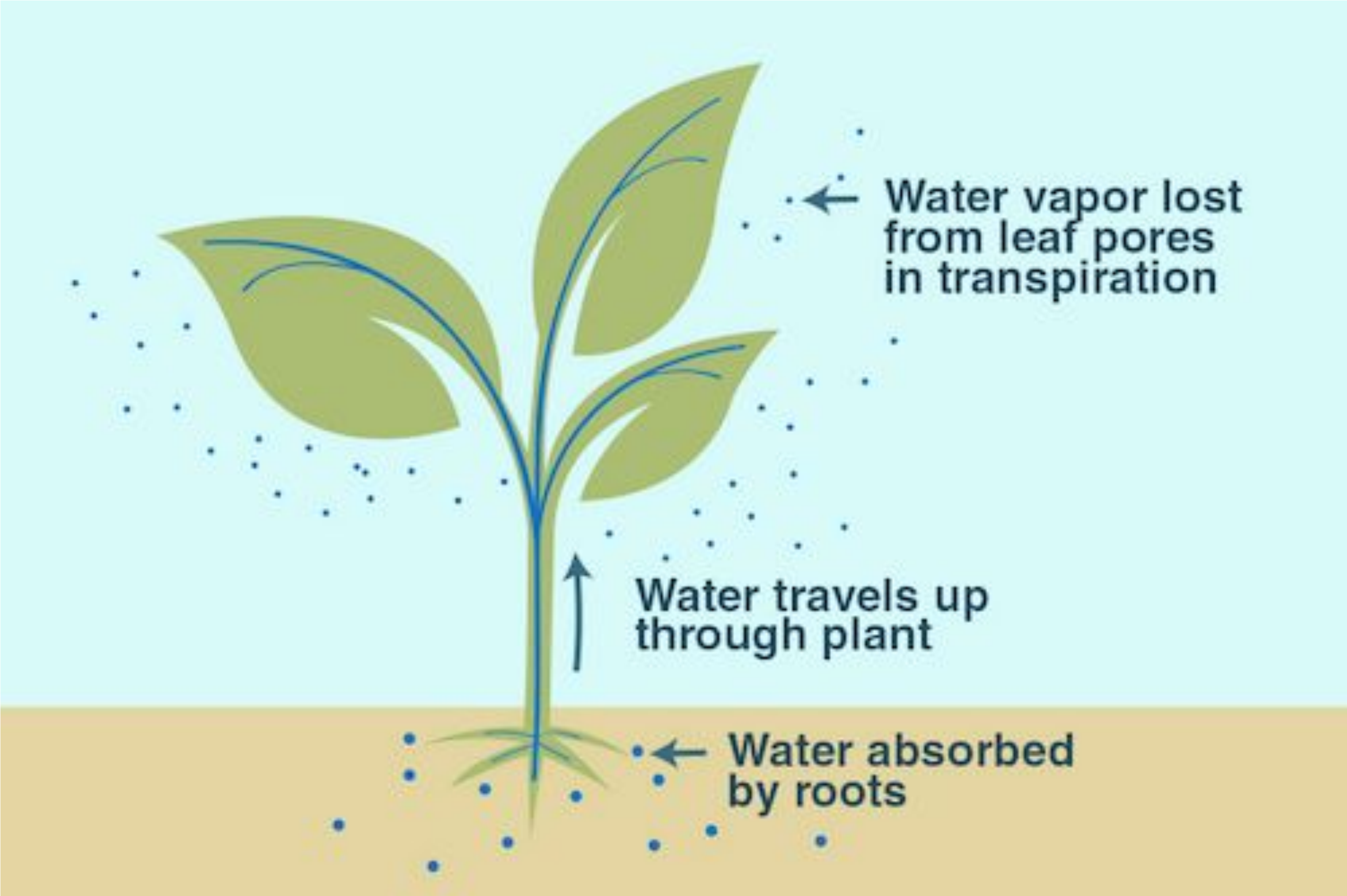
- Enhanced deposition of air pollutants to vegetated areas
  - Reduction of their concentrations
- Reduction of carbon dioxide (CO_2) concentration
  - Due to reduced building energy consumption
    - Evapotranspiration
  - Plants and vegetation absorb significant quantities of CO_2 through photosynthesis

More on **water quality benefits** of GRs

- Regulating effect on runoff water volume
  - Mitigation of pluvial floods
  - Improvement of runoff water quality
    - Reduced presence of urban stormwater pollutants
      - Plants and soil substrate
        - Absorb and filter pollutants
        - Act as sinks for nitrate and ammonia nitrogen

More on **ecosystem benefits** of GRs

- Increase in biodiversity
- Renaturing of cities


Water vapor lost from leaf pores in transpiration
Water travels up through plant
Water absorbed by roots

Social, aesthetic & psychological benefits of GRs

- Refuge of peace and tranquility
  - In the heart of urban environment
  - Less noise and pollution
- Contributing to psychological, physical health, and well-being improvements

Class discussion

- Do you think GRs/GFs should be **mandatory** in urban areas?
- Who should bear the **cost** of implementing GRs/GFs?
    - (Federal) government
    - Local government/authorities
    - Private owners
    - Shared model
- What do you see as the greatest **barrier** to widespread adoption of GRs/GFs?

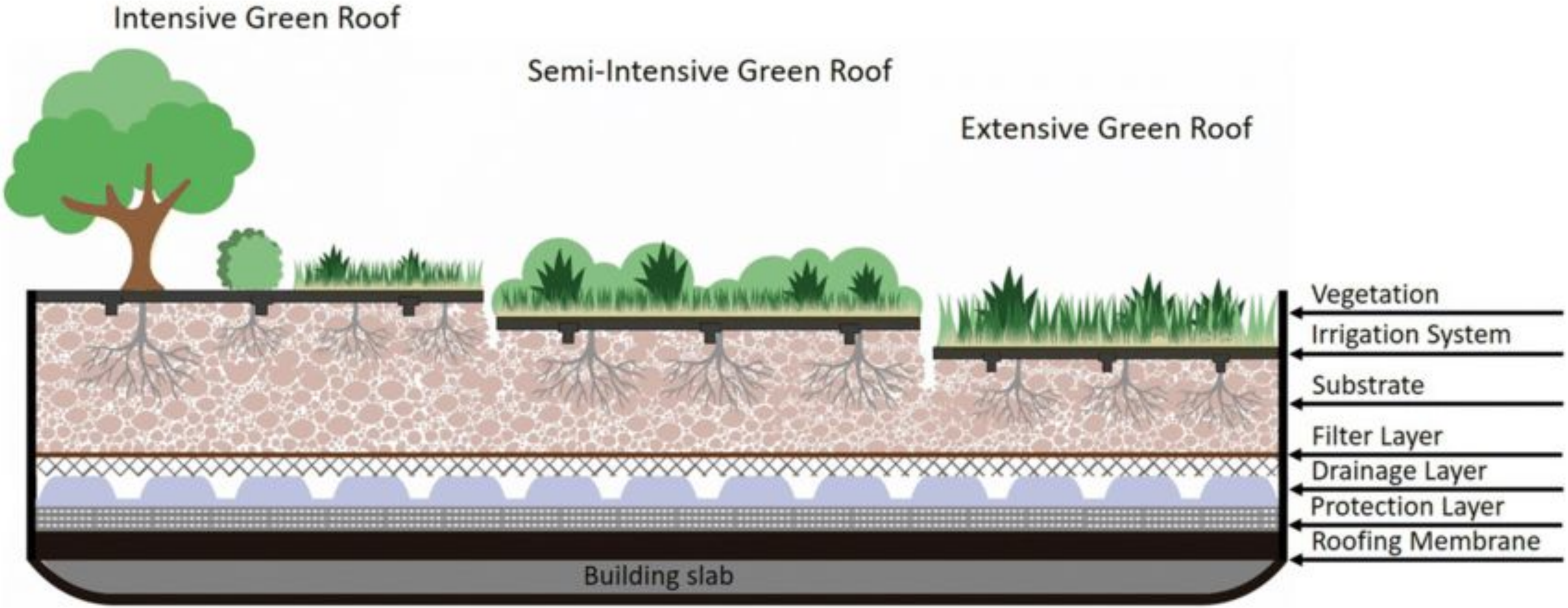
Write in chat

- What do you believe are the most important **sociopolitical considerations** for expanding GRs and GFs in urban settings?
  - Be brief, e.g. Social equity

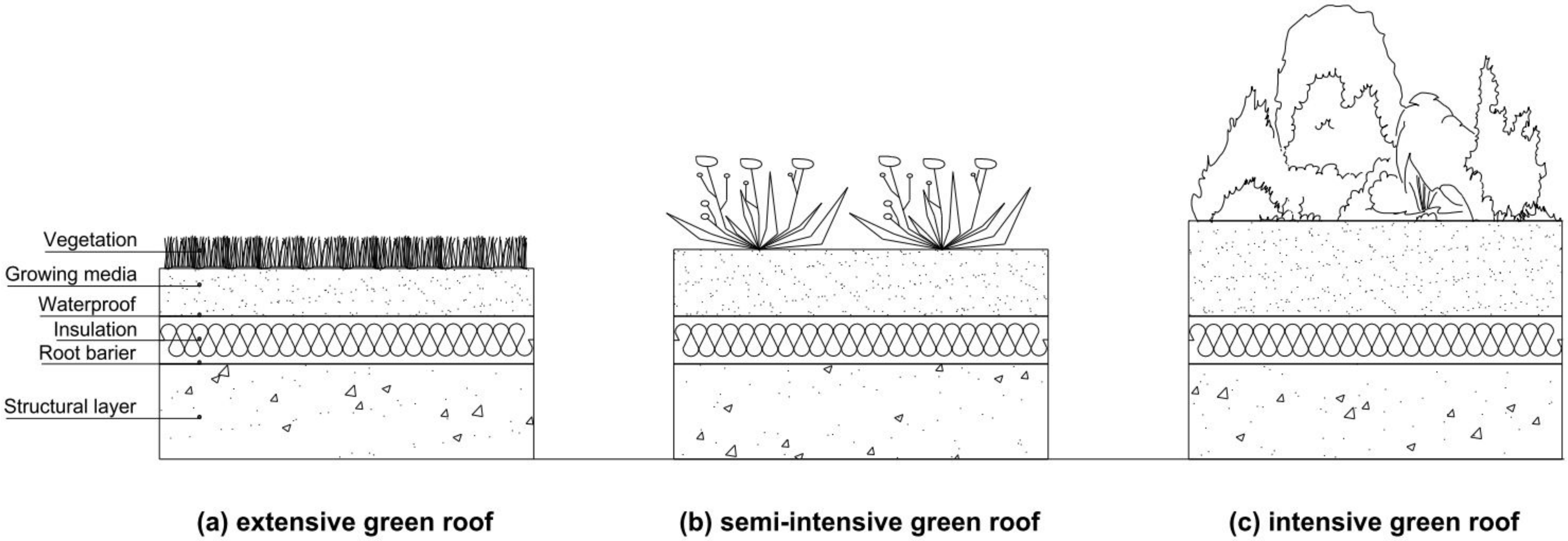
Ensuring that benefits are accessible to all socioeconomic groups, not just wealthier communities

The three types of GRs

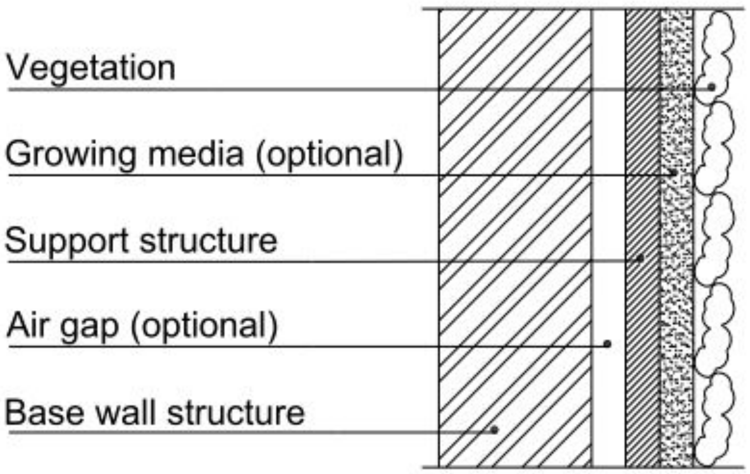
- **Extensive**
  - Shallow soil depth (<20 cm)
  - Vegetation requiring little maintenance
    - Short plants, grasses, herbs, short-grasses, mosses
  - No permanent irrigation system
- **Simple or semi-intensive**
  - Small plants, grasses, lawns, small shrubs
  - Require moderate maintenance and occasional irrigation
- **Intensive**
  - Deep substrates reaching a depth of 1 m
  - Support bigger plants
  - Large shrubs, grassland, flowerbeds, even trees
  - Require systematic maintenance and irrigation



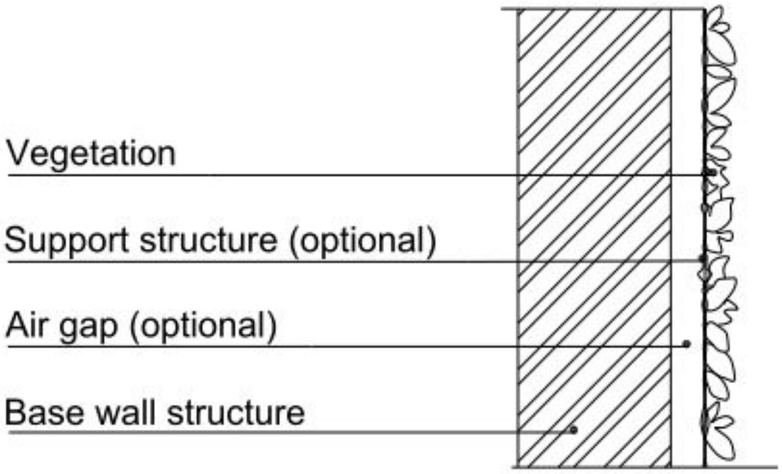
Intensive Green Roof
Semi-Intensive Green Roof
Extensive Green Roof
Vegetation
Irrigation System
Substrate
Filter Layer
Drainage Layer
Protection Layer
Roofing Membrane
Building slab



Harbiankova, A. & Manso, M. (2024), Integrating green roofs and green walls to enhance buildings energy efficiency: A literature review, submitted to *Building & Environment*



(d) living wall



(e) green facade

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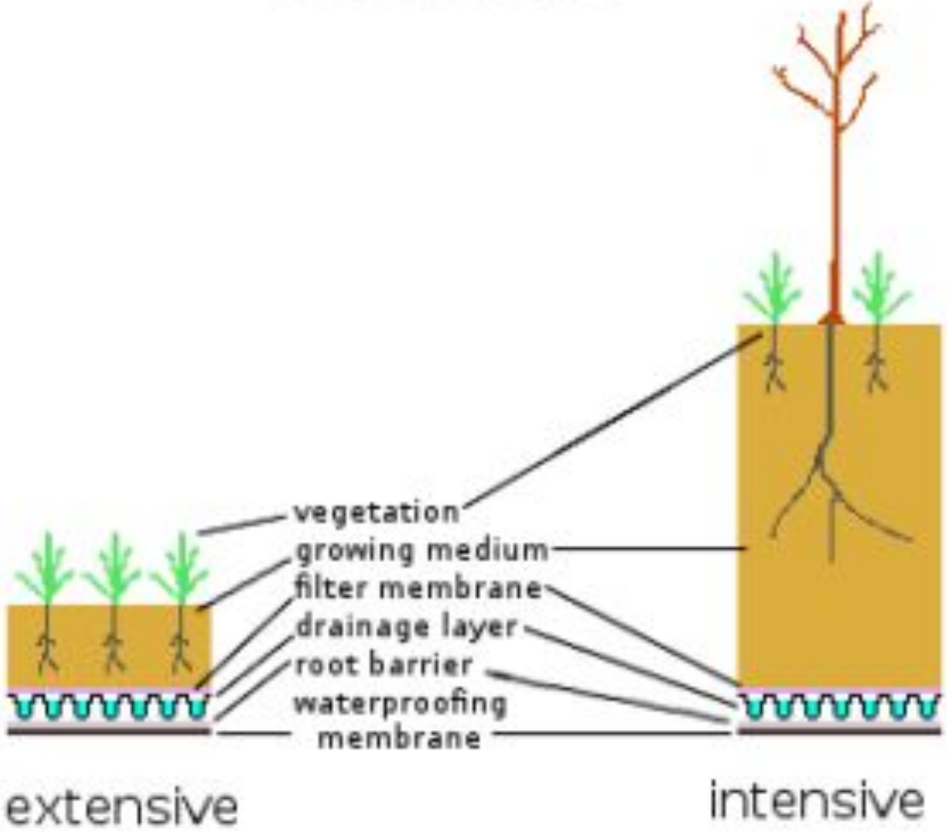
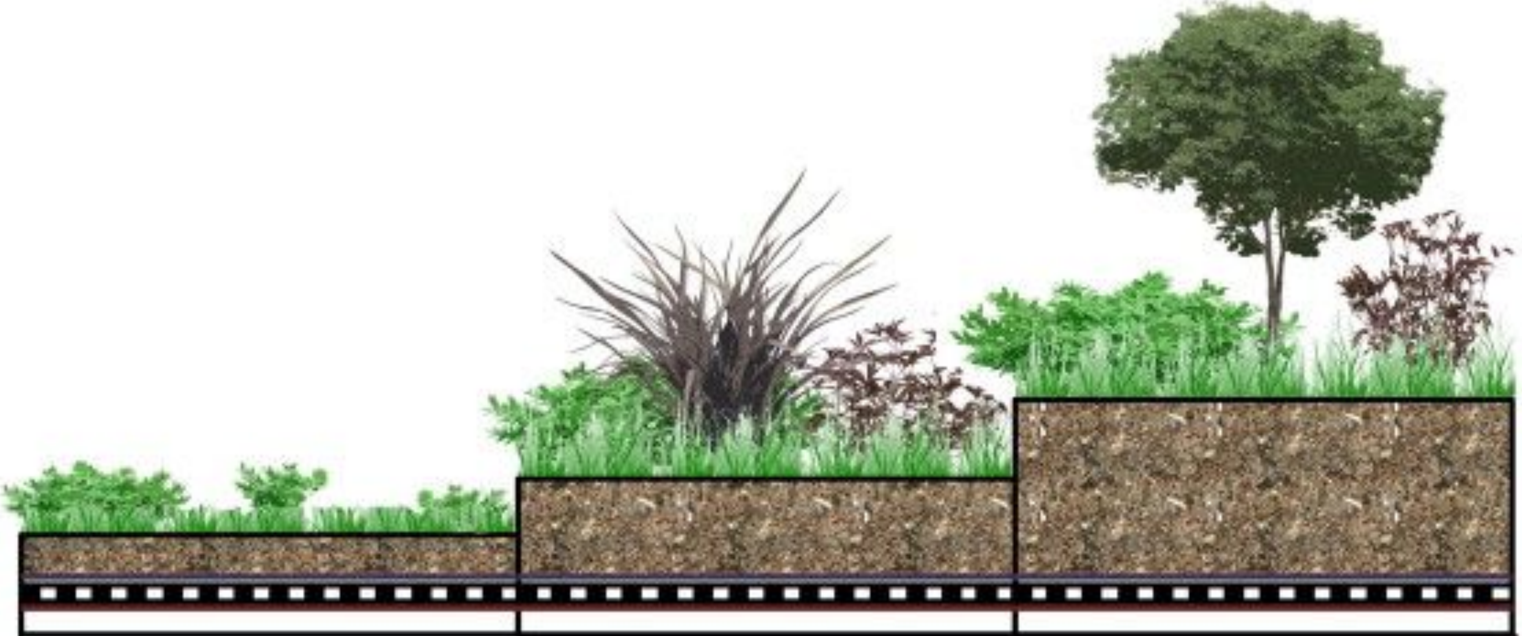
Green roofs:

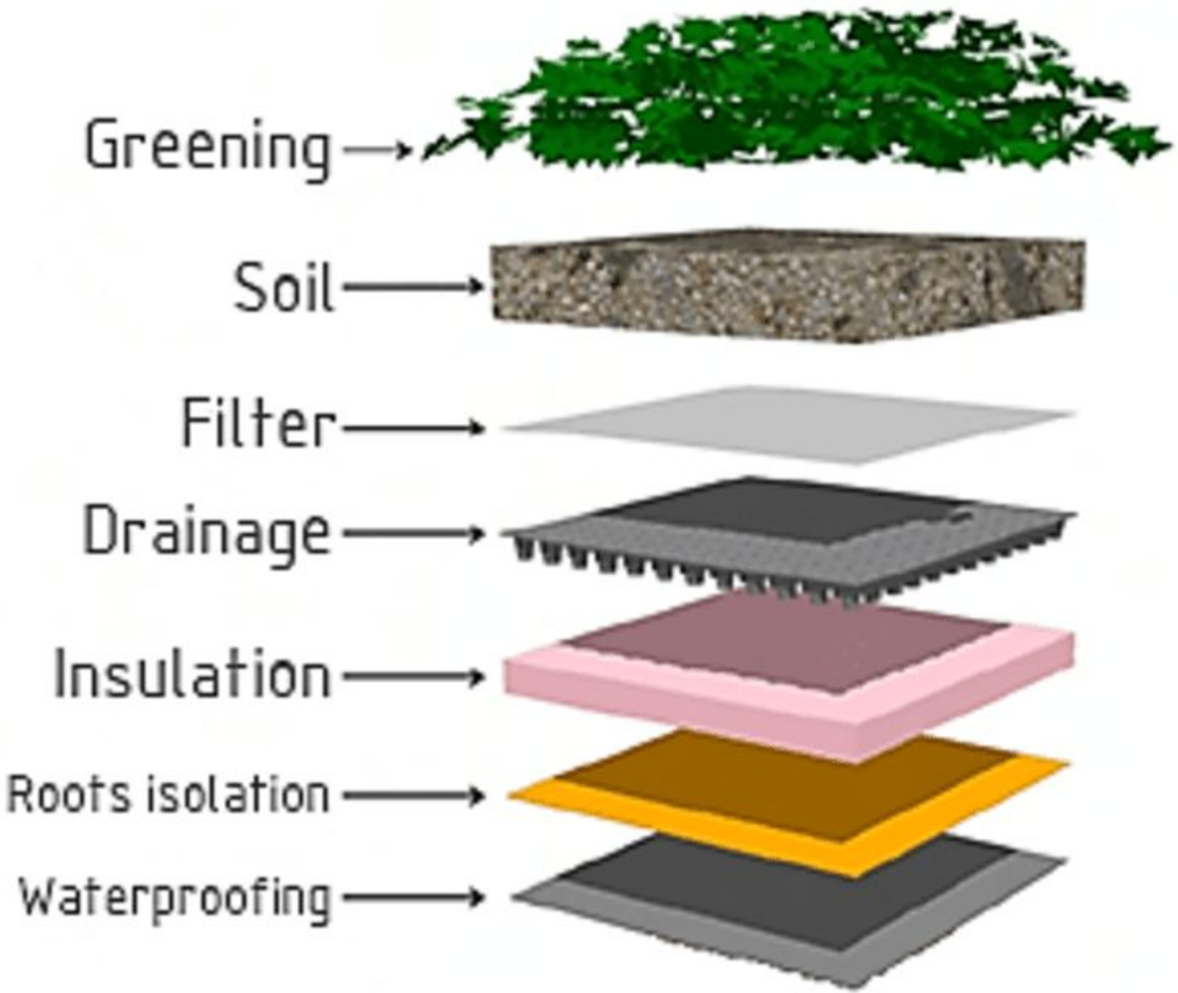

vegetation
growing medium
filter membrane
drainage layer
root barrier
waterproofing
membrane
extensive
intensive



EXTENSIVE GREEN ROOF	SEMI-INTENSIVE GREEN ROOF	INTENSIVE GREEN ROOF
Height: 6- 20 cm	**Height** : 12 - 25 cm	**Height** : 15 cm > 1m
Weight: 60 - 150 kg/m^2	**Weight** : 120 - 200 kg/m^2	**Weight** : 180 - 500 kg/m^2
Vegetation: mosses, sedums, herbs and grasses	**Vegetation** : grasses, herbs and shrubs	**Vegetation** : lawn, perennials, shrubs and small trees
Cost: low	**Cost**: middle	**Cost**: high
Maintenance: low	**Maintenance** : periodically	**Maintenance** : regularly

Components of GRs

- **Vegetation**: Plants improve air quality, improve runoff quality, and conserve energy
- **Soil layer**: Growth substrate characteristics are important GR parameters
- **Filter layer**: Supports GRs and separates soil and drainage material
- **Drainage material**: Supports GRs, provides necessary balance between air and water systems and improves thermal characteristics of GRs
- **Root barrier**: Prevents roof structure damage by plant roots
- **Waterproofing layer**: Essential for protection and insulation


Greening
Soil
Filter
Drainage
Insulation
Roots isolation
Waterproofing

The **thermal transmittance** (**U-value**) of a GR measures its ability to conduct heat and is measured in watts per square meter per degree Kelvin (W/m^2K)

- Watts (W): Rate of heat transfer
  - Higher wattage means that more heat is passing through the material per second
- Square meter (m^2): The U-value is normalized per unit area of the material
  - Represents heat transfer for each square meter
- Kelvin (K): Temperature difference across the material

Thermal transmittance (**U-value**) of GRs (continued)

U-value measures

- How much heat flows through the GR
- For each degree of temperature difference between the inside and outside

For example, a U-value of 2 W/(m^2K) means that

- For every degree (°) difference between the inside and outside temperature of a GR
- 2 watts of heat energy are transferred per m^2 of the GR

Lower U-values indicate better insulation (less heat is transferred)

Thermal transmittance (**U-value**) of GRs

- Depends on several factors
  - Thickness of soil and vegetation layer
  - Plant type
  - Underlying roof structure

U-values

- Range between 0.1 and 0.3 $W/(m^2K)$ for extensive GRs
- Can be lower (more insulating) for intensive GRs
- Standard roofs without insulation often have much higher U-values
  - Around 1.0 $W/(m^2K)$ or higher

Important GR parameters

- **Leaf Area Index** (LAI)
  - Characterizes plant canopy
  - Ratio of the (one-sided) leaf area to the unit ground surface area
    - Example: A plant canopy has a total leaf area of 10 m^2 over a 1 m^2 ground area
      - LAI = 10 m^2/1 m^2 = 10 (dimensionless)
  - Large contribution to shading and evapotranspiration
    - One of the primary GR system variables impacting the thermal behavior of a GR system

More important GR parameters

- Type of GR
- Plant coverage
- Foliage height and density
- Soil layer thickness
- Evapotranspiration rate
- Irrigation
- Roof insulation (thickness)
- Climatic parameters
  - Incident solar radiation
  - Ambient air temperature
  - Air relative humidity
  - Wind speed

20 to 25% of total urban surface are comprised by roofs

- This provides a significant benefit for greening space in the urban environment

Numerous studies have investigated the role of GRs in

- Reduction the energy demand for heating and cooling
  - Resulting in a decrease of energy consumption
- Regulating indoor air temperature
  - Improving thermal comfort

GRs are a part of the building envelope and play a significant role in

- Energy efficiency
- Thermal comfort

The energy performance of GRs depends on

- Type of GR (intensive, extensive, etc.)
- Type of vegetation
- Climatic conditions
- Shape and characteristics of the building

Research findings

- GRs contribute to a substantial (up to 70%) decrease in the cooling load and a 10 to 60% increase in annual energy savings
- GRs are projected to be able to reduce the indoor air temperature by up to 15°C
- GRs with trees outperformed simple GRs (even when the latter had greater coverage)
- By shading a building with nearby trees, it was possible to reduce further the internal temperature
- The combination of GR and green walls can achieve a greater reduction of indoor temperature and improve thermal comfort

In-class investigation

- Search for countries that are active in GR policies
- Select one and present to the class
  - Strategies
  - Policies
  - Challenges

Then, the instructor will present one of his favorites

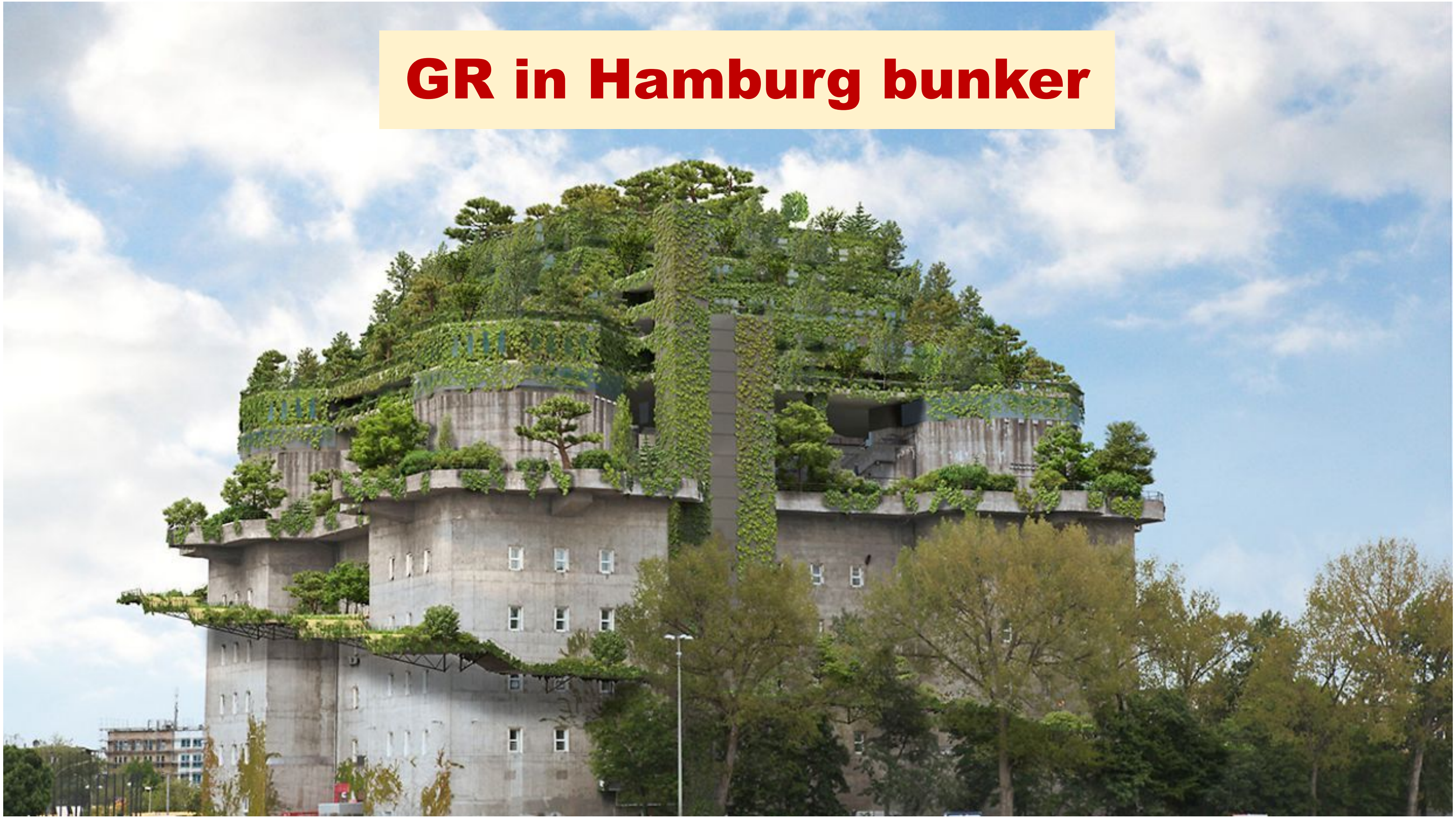
Germany

- **Development plans**: About two-thirds of German cities have made GRs mandatory (2019)
- **Mandates and building codes**: Some German cities, like Stuttgart, have made GRs mandatory for flat-roofed commercial and industrial structures
- **Incentives and subsidies**: Local governments often offer financial subsidies covering 50 to 100% of the installation costs of GRs
- **Stormwater management**: Some policies offer reduced stormwater fees for buildings with GRs

Germany (continued)

- **Energy efficiency and climate goals**: GRs are encouraged as part of Germany’s broader energy efficiency and climate targets
- **Biodiversity promotion**: In some cases, German policy requirements specify plant types or designs that support biodiversity
- **Public awareness and research**: German organizations and government bodies often partner to demonstrate the benefits of GRs

GR in Hamburg bunker



Stuttgart – Green Roof Capital of Europe

Back-of-the-Envelope Calculations

About 56% of global **population** lives in urban areas (2024)

- This amounts to approximately 4.4 billion people

Around 8% of the global population lives in megacities (2024)

- Cities with over 10 million residents

Cities

- Cover only around 3% of the Earth's land area
- Are responsible for about 70% of global greenhouse gas emissions
  - Due to concentration of industries, transportation, building energy use, and waste generation

Percentage of urban land area occupied by **roofs**

- Varies significantly based on the density and layout of the city
  - In densely developed urban centers like New York City, roofs can cover approximately 20 to 25% of total land area
    - New York City is reported to have over one million rooftops
  - In less dense cities or suburban areas, roof coverage as a percentage of land area is generally lower, ranging from 10 to 15%

Roofs and **pavements**

- Collectively occupy approximately 40 to 60% of a city's total land area, including
  - Rooftops (which alone can cover about 20 to 25% of land area in dense urban centers)
  - Pavements, such as roads, sidewalks, and parking lots, which can take up an additional 20 to 35%

Greenhouse gas (GHG) emissions from urban areas can be expressed on an areal basis

- Typically tons of CO_2 equivalent per square kilometer per year ($tCO_2e/km^2/year$)
- High-density cities (such as New York City or Tokyo) tend to have high emissions per square kilometer
    - They are more likely to benefit from energy-efficient infrastructure that reduces per capita emissions
- Low-density urban (and suburban) areas might have lower emissions per square kilometer
    - But they have higher per capita emissions due to reliance on personal vehicles and less efficient infrastructure

Calculations

- Assume 40% of urban GHG emissions come from buildings
  - Mostly heating and cooling
- Assume 25% average rooftop coverage in urban areas
  - GRs could theoretically cover that
- Studies show that GRs could reduce energy demand for heating and cooling by 15% (for insulated buildings)
- GRs would only be on that 25% of building space in a city
  - The overall effect on total building-related GHG emissions would be 15% of that 25%
    - $15\% \times 25\% = 0.15 \times 0.25 = 0.0375 = 3.75\%$
- But only 40% of urban emissions come from buildings, so
  - $3.75\% \times 40\% = 0.0375 \times 0.4 = 0.015 = 1.5\%$

Conclusions

- Converting all suitable rooftops to GRs might yield an overall **1.5% reduction in urban GHG emissions**
  - This is based on the building emissions reduction from energy savings alone
  - There are additional benefits from **CO_2 sequestration**
- GRs can also sequester CO_2 through the plants grown on them
  - To calculate the impact of CO_2 sequestration we would have to assume a specific area (in m^2)

Let's assume an area of **10 million square meters** (10 km^2)

- Relatively small for an entire city
- Could represent a district or neighborhood within a larger city

Here are a few urban examples for perspective

- Central Park, NYC, about 3.4 km^2
- City of London, historic core and financial district, close to 2.9 km^2
- Downtown Los Angeles, around 15 km^2
- Paris's 1st Arrondissement (includes parts of the Louvre and the historic city center), about 1.83 km^2
- Singapore's Marina Bay, a major commercial and recreational area, about 3.5 km^2

Singapore's Marina Bay

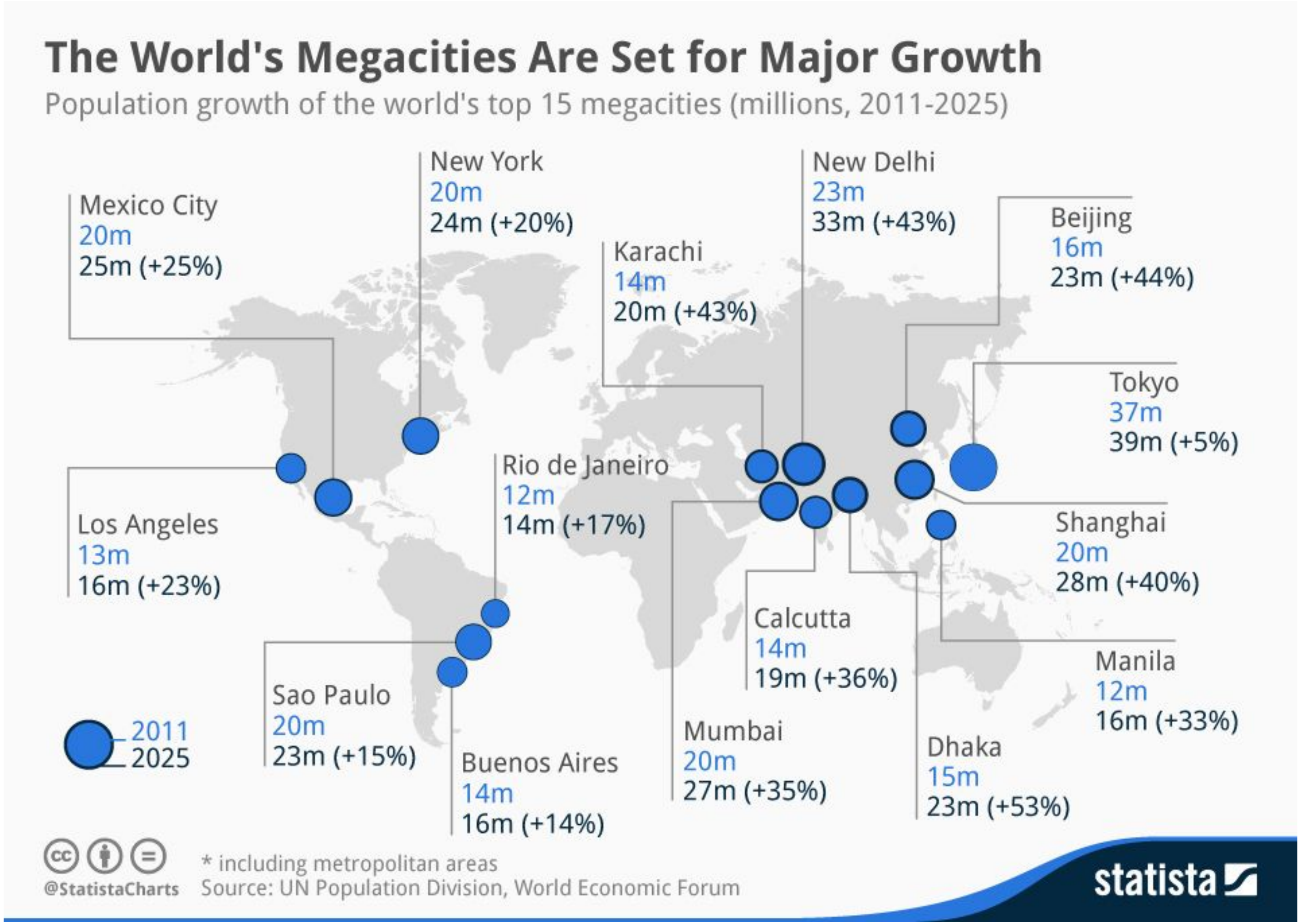
CO_2 sequestration calculations

- A typical GR might sequester 0.5 to 1 kg of CO_2 per m^2 per year
- For a city with 10 million m^2 of rooftop area, this could mean
  - $10{,}000{,}000\ m^2 \times 0.75\ kg\ CO_2/m^2/year = 7{,}500{,}000\ kg\ CO_2/year = 7500$ tons of CO_2/year
- **Greece**'s annual 2022 GHG emissions were 77 MtCO2-eq
  - 7500 tons of CO_2/year represent
    - $(7500/77{,}000{,}000) \times 100 = 0.00974\% \approx 0.1\%$
- But this would be coming from a relatively small urban area of 10 km^2

Scale up this potential CO_2 reduction from GRs to the entire urban area of Greece

- The urban area of Greece is approximately 2500 km^2 (including metropolitan areas like Athens and Thessaloniki)
  - Assume that 25% of that urban area is covered by rooftops
- Reduced emissions from energy savings
  - 900,000 tons/year *(details omitted)*
- Potential CO_2 sequestration
  - 468,750 tons/year *(details omitted)*
- Total reduction
  - 468,750+900,000 = 1,368,750 tons of CO_2/year
- Percentage of Greece's annual 2022 GHG emissions
  - $(1,368,750/77,000,000) \times 100 = 1.778\% \approx 1.8\%$

Let's consider GRs in **megacities**



GRs and **megacities**

- In megacities like Tokyo, New York, and Mumbai, the **urban heat island** (UHI) effect is intense because of dense infrastructure, minimal green spaces, and high energy use.
    - Studies in cities like Toronto and Singapore reveal that GRs can lower rooftop temperatures by up to 22°C
        - Cools individual buildings
        - Contributes to a cooler citywide microclimate
- Megacities like Jakarta, Manila, and São Paulo experience severe **flooding** due to high rainfall and extensive impermeable surfaces
    - GRs retain stormwater, reducing the volume of runoff reaching overburdened drainage systems
    - Research in Beijing has demonstrated that a network of GRs can absorb up to 50-70% of rainfall during heavy storms
        - GRs act as a decentralized sponge that helps mitigate flood risks

GRs and **megacities** (continued)

- **Pollution** levels in megacities such as Delhi, Mexico City, and Bangkok often exceed safe limits
    - GRs can act as air purifiers, filtering out pollutants like carbon dioxide, sulfur dioxide, and particulate matter (PM2.5 and PM10)
    - Studies from European megacities show that dense GR coverage can reduce urban concentrations of particulate matter by up to 20%
- Megacities often lack **biodiversity** due to urban sprawl and habitat loss
    - GRs in cities like Paris, London, and Los Angeles provide critical “stepping-stone” habitats for pollinators and other urban wildlife
        - GRs create biodiversity corridors across rooftops
        - In dense urban settings, even a small network of GRs can reconnect fragmented ecosystems

GRs and **megacities** (continued)

- Climate change brings **extreme weather events** that hit megacities especially hard due to high population densities and vulnerable infrastructure
  - In **coastal megacities** like Miami and Shanghai, GRs add resilience by reducing building energy needs during heatwaves, decreasing flood risks, and mitigating wind effects on high-rise structures
    - Studies on GRs in Singapore show that they can reduce cooling energy consumption by 25%
      - Enhances the ability of buildings to endure climate extremes
      - Reducing energy strain across the grid

Let’s close with some amazing GRs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