Evidence-based urban green infrastructure planning in humid sub-tropical neighbourhoods to enhance outdoor thermal comfort

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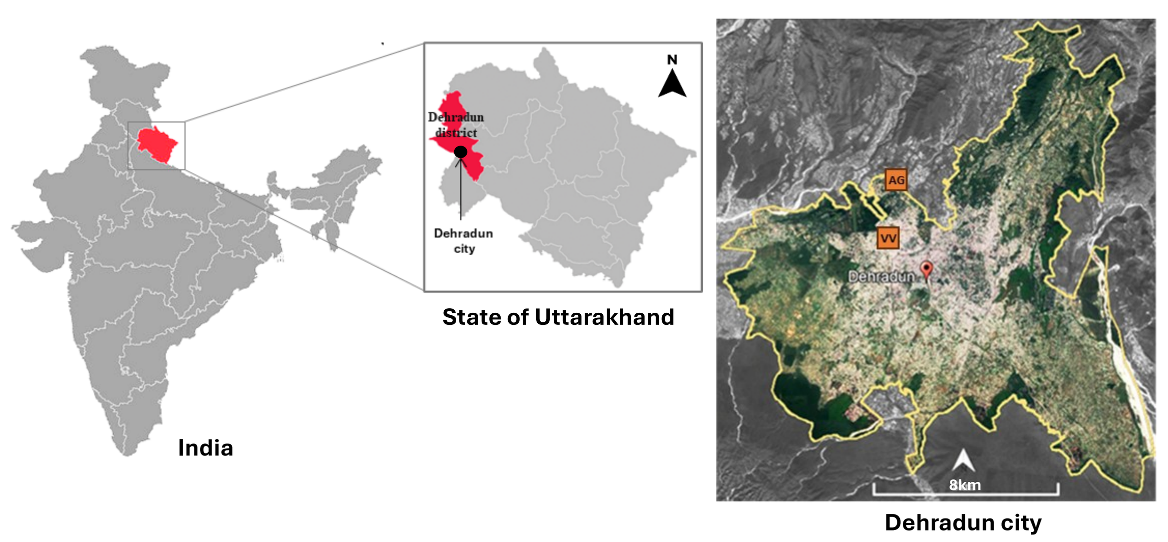
BACKGROUND

Humid sub-tropical urban areas grapple with **extreme heat stress** in peak summers exposing the inhabitants to **higher health risks and lower quality of life**

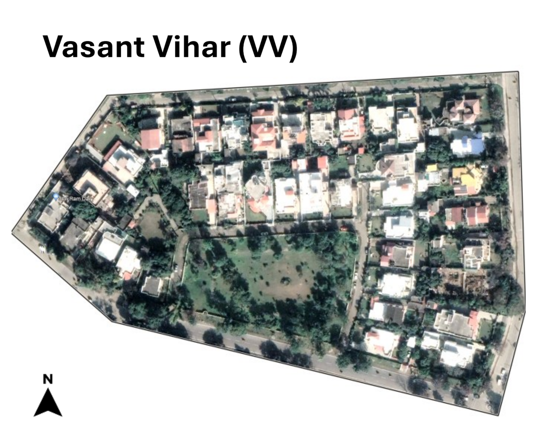
But heat mitigation potential of urban green infrastructure (UGI) remains **untapped** in most of the **Indian cities** due to **lack of actionable evidence**

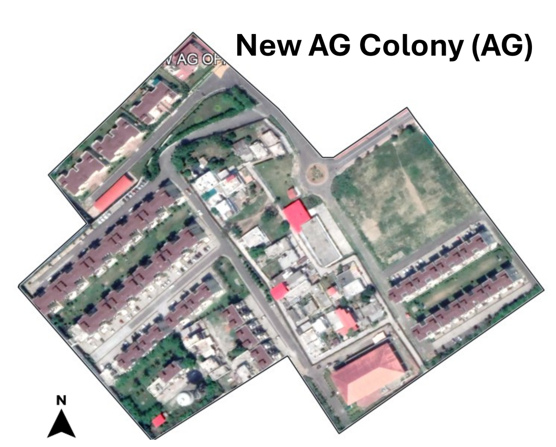
STUDY AREA

North Indian city of Dehradun



Two typical residential typologies with **community park, streetside plantation** and **private gardens/shared courtyards**





Individual detached houses (3–11m) with **private gardens**

4.9h site area — **23% built up**, 26% surface sealing, **33% canopy cover (CC)**

Row block houses (3–13m) with **shared courtyards**

6.7h site area — **20% built up**, 35% surface sealing, **24% canopy cover**

RESULTS of microclimatic simulations using validated ENVI-met software

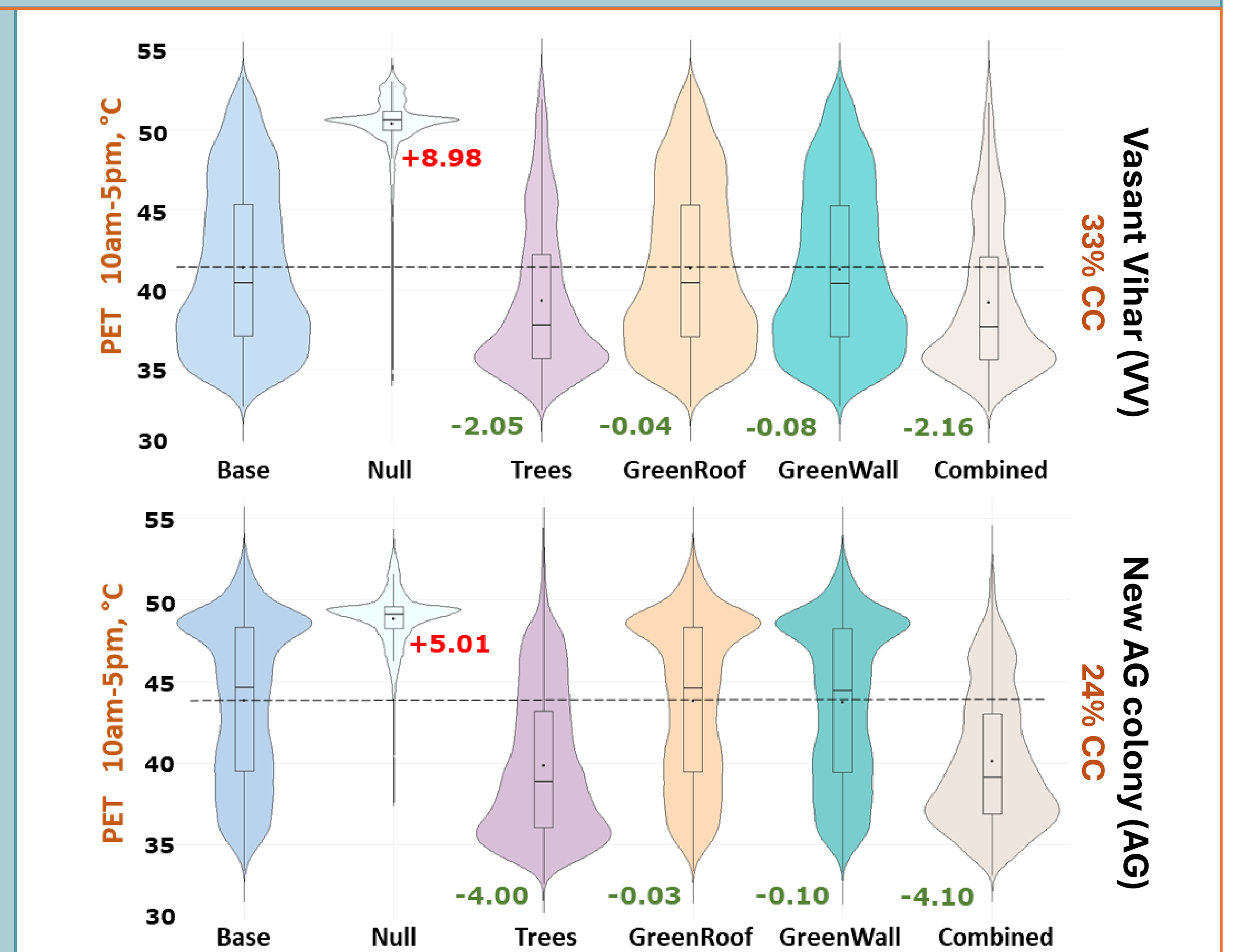
Basecase: Existing situation (irrigated and non irrigated)

Nullcase: No vegetation (reference scenario)

4 UGI type scenarios on VV and AG site each:

Sc. 1: Only trees, **Sc. 2**: Only Green roofs (GR),
Sc. 3: Only Green walls (GW), **Sc. 4**: Combined (Trees+GR+GW)

'Right' UGI Type



Note: Avg. PET change is indicated in red and green colour text w.r.t. basecase

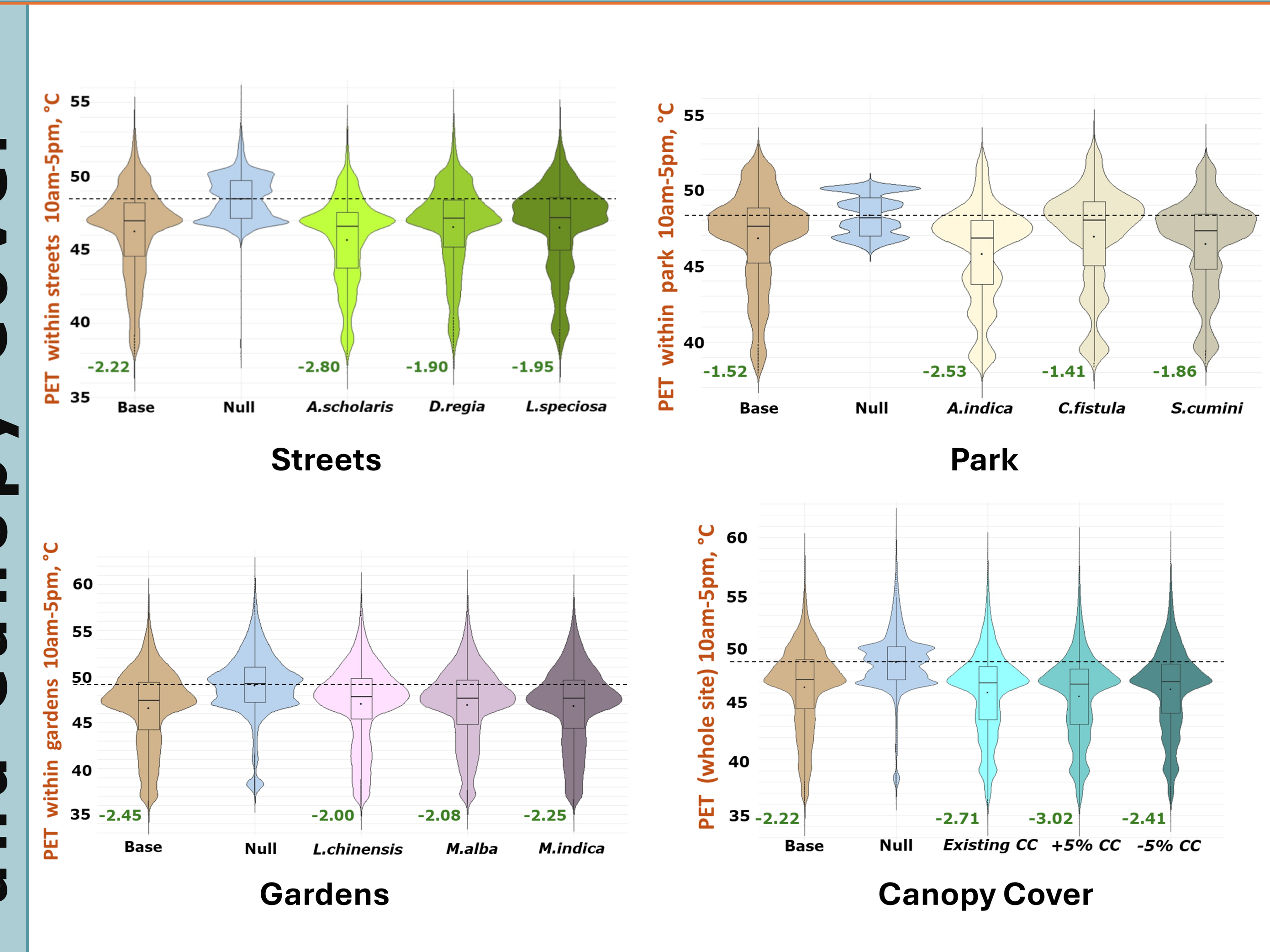
9 subtropical tree species scenarios on VV site:

Streets: *Alstonia scholaris, Lagerstroemia speciosa, Delonix regia*
Parks: *Azadirachta indica, Syzygium cumin, Cassia fistula*
Gardens: *Mangifera indica, Litchi chinensis, Magnolia X alba*

3 canopy cover scenarios:

Existing CC with best trees (33%), **+5% CC** (38%), **-5% CC** (28%)

'Right' Tree Species and Canopy Cover

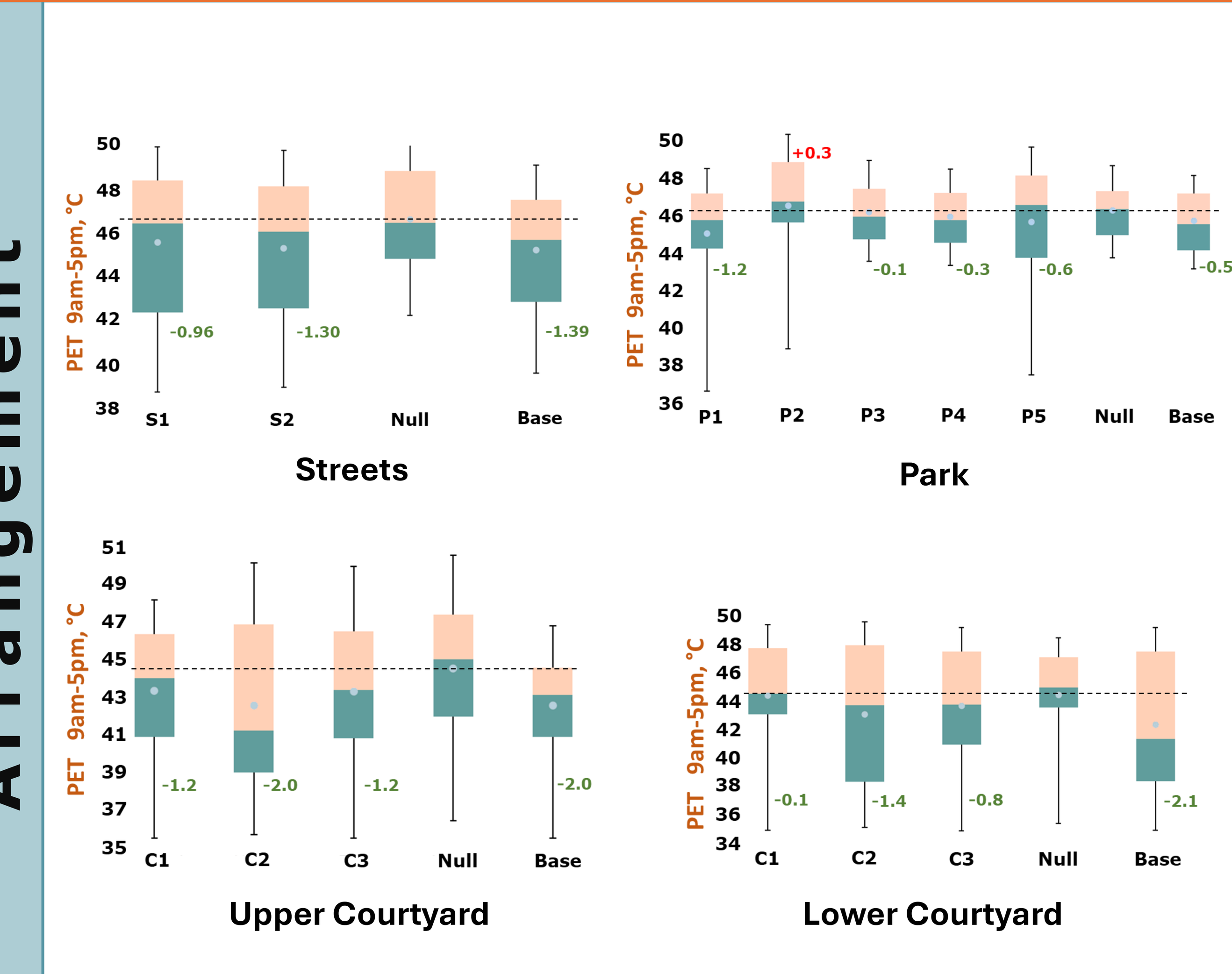


Note: Avg. PET change is indicated in green colour text w.r.t. nullcase

10 planting arrangement scenarios on AG site:

Streets: **S1**: 1 tree on each side in staggered pattern, **S2**: 2 trees on one side
Parks: **P1**: 2 double row of trees parallel to wind, **P2**: 2 double row of trees perpendicular to wind, **P3**: Full rectangular, **P4**: Peripheral without one side, **P5**: Clusters
Courtyards: **C1**: Staggered, **C2**: Middle, **C3**: Edge

'Right' Planting Arrangement



Note: Avg. PET change is indicated in red and green colour text w.r.t. nullcase

INFERENCES

UGI type

- **Trees cool substantially better** than green roof and walls. **Cooling intensity increases** with **soil irrigation and strategic planning** i.e. on using best tree species and best planting arrangement
- **Green walls perform marginally better than green roofs** but still offer **limited heat mitigation potential in outdoor areas**

Subtropical tree species and canopy cover

- ***Alstonia scholaris, Azadirachta indica and Mangifera indica*** exhibit **maximum daytime cooling** in streets, park and gardens respectively, attributed primarily to **traits** like **canopy density and height**
- **Cooling efficacy** of trees **varies** within **different spatial setups**
- **OTC increases** with **canopy cover** and is **better** with **optimal tree species** i.e. **canopy quality** is more impactful than **canopy quantity**

Planting arrangement

- **Tree arrangement influences shade, wind speed and direction** on the site. Thus, **patterns parallel to wind or facilitating wind flow and widespread shade cool better** as evident in **scenarios S2, P1 and C2**

Note: Outdoor thermal comfort (OTC) is evaluated using thermo-physical index **PET (Physiological equivalent temperature)** averaged over daytime to understand the shading pattern throughout the heat stressed period instead of a single hour

Abstract

The presentation participates in OSPP — EGU — Outstanding Student & PhD candidate Presentation contest

Sharing not permitted

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Technische Universität München
DAAD Deutscher Akademischer Austauschdienst German Academic Exchange Service
DLGS Dresden Leibniz Graduate School
Leibniz Institute of Ecological Urban and Regional Development

URBAN OASIS

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Supplementary material

OUTLINE

1. Introduction

Background

Aim of the study and Research questions

2. Methodology

Study area

Microclimatic simulations

Scenario design

Analysis

3. Results and Discussions

4. Conclusion

Background

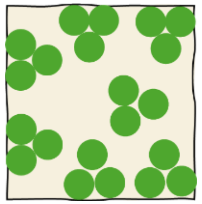
Urban Green Infrastructure based Heat Mitigation

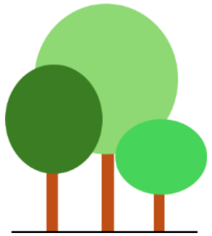
Unimpeded **urbanisation**, **anthropogenic activities**, **lack of** adequately planned **green spaces** (Singh 2013), (Bartesaghi Koc 2018)

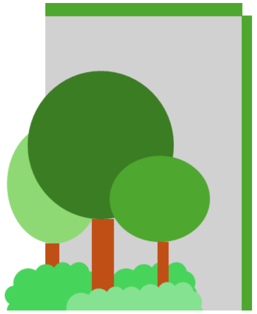
Heat stress and thermal discomfort – exacerbated in **humid-sub tropical developing countries** (Bartesaghi Koc 2018)

Decreased usability of outdoor spaces, **declined well-being** and **liveability** (Nazarian 2019)

Increased **health concerns** and **mortality rate** (WHO 2018), (Guleria 2018)







Urban green infrastructure (UGI) supports climate adaptation incl. **heat mitigation** (Zölch 2016)

Cooling impact varies with **UGI type and planning strategy** like **tree arrangement, canopy cover** etc. (Zölch 2016), (Zölch 2019)

Lack of evidence on the role of **diverse UGI types and planning strategies** in **realistic urban settings** with distinct morphologies (Norton 2015), (Zhang 2019), (Erlwein 2021)

Need to **contextualise and strategically plan UGI** for **different urban and climatic contexts**

Aim of the study

To investigate different **urban greening strategies** for enhancing **outdoor thermal comfort** in **humid subtropical** residential neighbourhoods: *Case of Indian city of Dehradun*

Research Questions

1. How do different **tree planting patterns** impact **outdoor thermal comfort (OTC)** in different **urban settings (streets, park, courtyards/gardens)** of a residential neighbourhood in **humid subtropical climate**?

2. What effect do different **subtropical tree species** have on OTC in aforementioned urban settings and which **structural tree traits** explain the cooling variation amongst these tree species?

3. What is the synergistic cooling impact on the site, when best tree species are planted in their respective urban settings, under varying **tree canopy cover** scenarios?

4. What is the individual and combined cooling potential of **different UGI types (trees, green roofs, green walls)** in realistic residential neighbourhoods in humid subtropical climate and does **strategic urban greening (best tree+best arrangement)** and **soil irrigation** enhance OTC?

Study Area

North Indian city of Dehradun

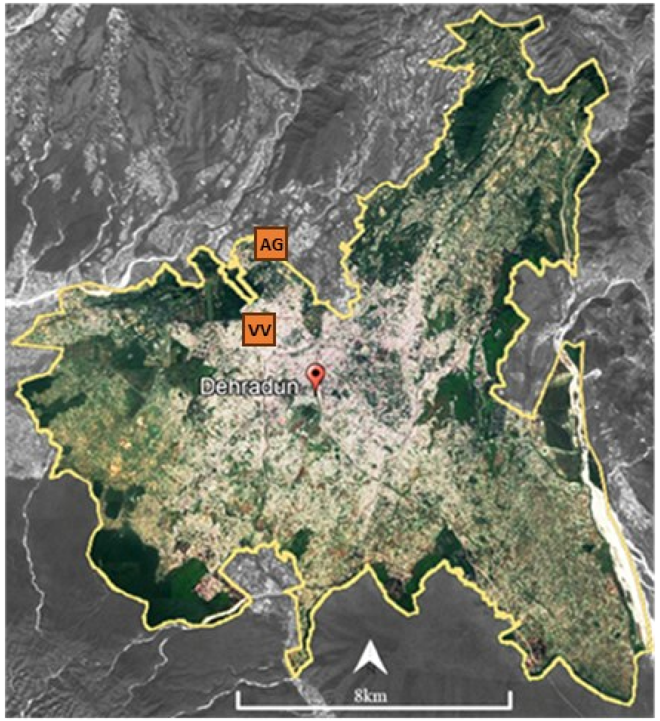
Humid-Subtropical Climate (Cwa)

Identifying residential typologies

_**Aerial imagery** (land cover land use) analysis & **field survey**

_**Typical typology** in Dehradun and other Indian cities

_Residential neighbourhoods with **park, streetside plantation, gardens or courtyards**



DEHRADUN CITY

Site 1: Vasant Vihar (VV)

Site 2: New AG colony (AG)

Greener site

Individual detached houses with private gardens

Less green site

Row block houses with shared courtyards

	VV	AG
Site area	**4.9h**	**6.7h**
Built-up area	23%	20%
Sealed surfaces	26%	35%
Unsealed surfaces	11%	7%
Canopy cover	**33.86%**	**23.79%**
Building height	3-11m	3-13m

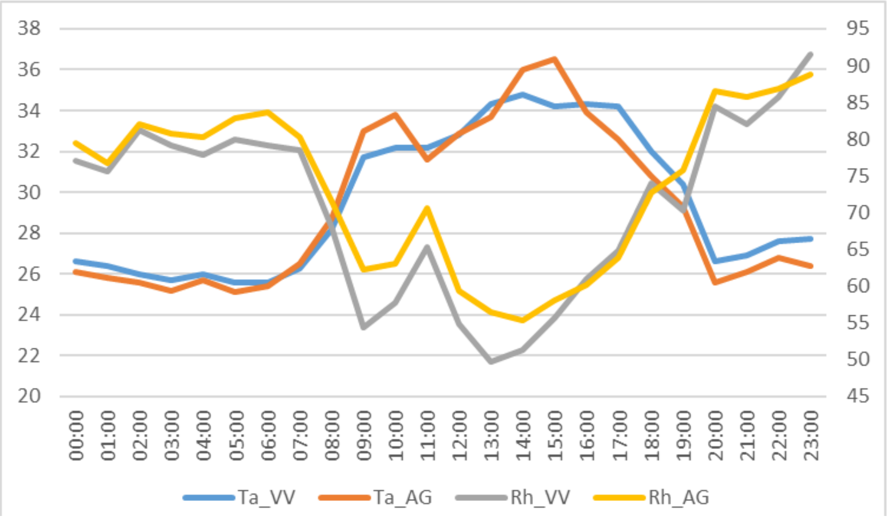
Google earth, Photos: Author

Microclimatic simulations

Field surveys - Collect **micrometeorological** and **land cover** (built, paved and vegetated) **data**

Greening scenarios - **Optimum planting arrangement, Subtropical tree species, Canopy cover** and **UGI types**

Model validation and simulation



ENVI-met (4.4.5 & 5.5.1)

Planting arrangement for different urban settings like courtyards/gardens, parks, streets

Tree species selection based on frequency (abundance in respective urban settings), shade potential (open canopy trees excluded), morphology and growth habit (shading trees and deciduous)

- Streets: *Alstonia scholaris, Lagerstroemia speciosa, Delonix regia*
- Parks: *Azadirachta indica, Syzygium cumin, Cassia fistula*
- Gardens: *Mangifera indica, Litchi chinensis, Magnolia X alba*

Canopy cover scenarios using best tree in respective urban settings

Diverse UGI types (Trees, Green roof, Green wall)

Simulation setup for 3rd July 2019 (Ta_Day>30ºC **Ta_Night**>20ºC**)**

Rh>50%
Ws 2-3m/s
Wd 116-158

Start and running time: 5am, 44h (2x2x2 resolution), Simple forcing

High correlation of 96% (Air temperature) and 90% (Relative humidity)

Analysis

Parameters

Physiological Equivalent Temperature (PET) at 1.4m height

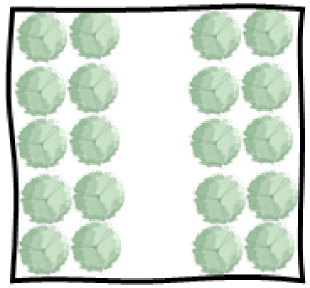
9 or 10 am to 5 pm

PET Range [°C]	<14	14-18	18-22	22-26	26-30	30-34	34-38	38-42	>42
Thermal perception	Very Cold	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot
Physiological stress	Extreme cold stress	Strong cold stress	Moderate cold stress	Slight cold stress	No thermal stress	Slightly heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

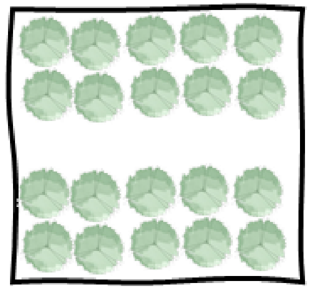
Planting arrangement scenarios

Planting arrangement scenarios

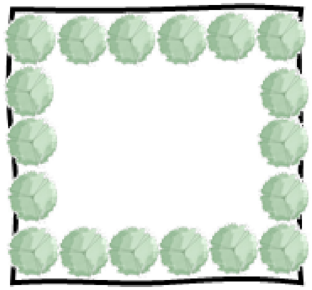
(Without soil irrigation)



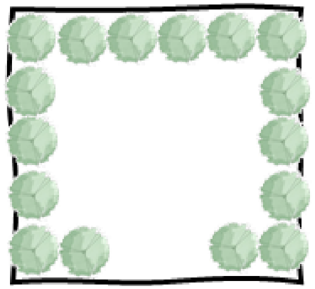
P1: Two double rows of trees parallel to prevailing wind



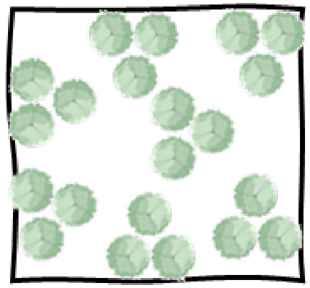
P2: Two double rows of trees perpendicular to prevailing wind



P3: Full rectangular

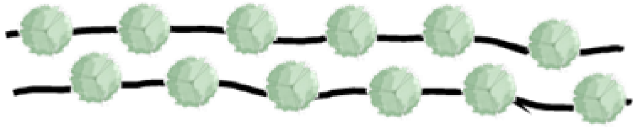


P4: Rectangular without one side

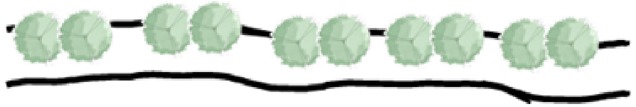


P5: Clusters

Park Scenarios

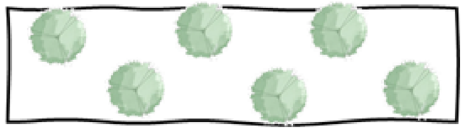


R1: Staggered tree pattern on both sides of road

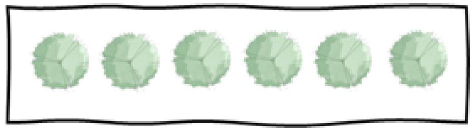


R2: Group of two trees on one side of road

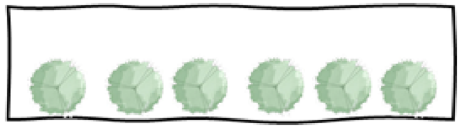
Streetside Scenarios



C1: Staggered plantation



C2: Middle plantation



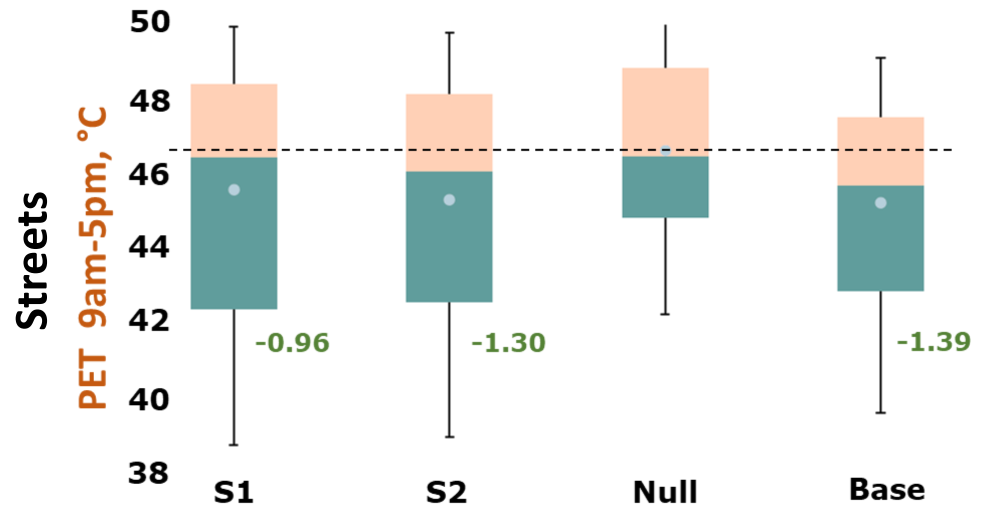
C3: Edge plantation

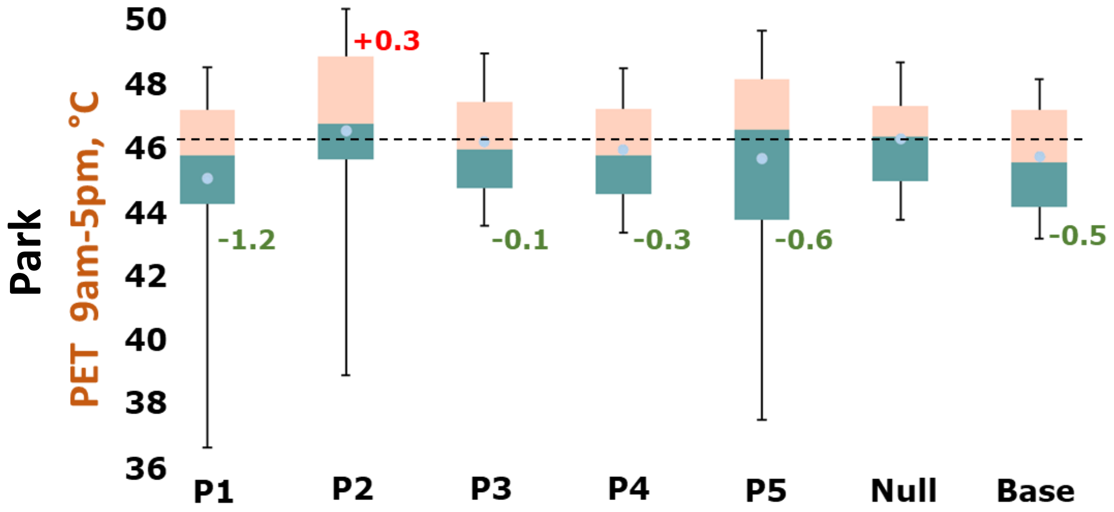
Courtyard Scenarios

Representation of plantation scenarios in the three urban settings (Not to scale or true north)

***Note:** Tree characteristics and total tree canopy area were kept constant to focus on the impact of the plantation arrangements

Planting arrangement





Note: Avg. PET change is indicated in red and green colour text w.r.t. nullcase

STREETSIDES

- Negligible air temperature reduction (<0.5°C) but **better mean radiant temperature reduction** (up to 3.5°C) between 9 am and 5 pm

OTC between 9 am to 5 pm

- **S2 showed better reduction** in mean PET (1.3°C) compared to S1 (0.96°C). Therefore, **group of two trees on one side more beneficial** for heat mitigation due to **higher potential to channel the wind**

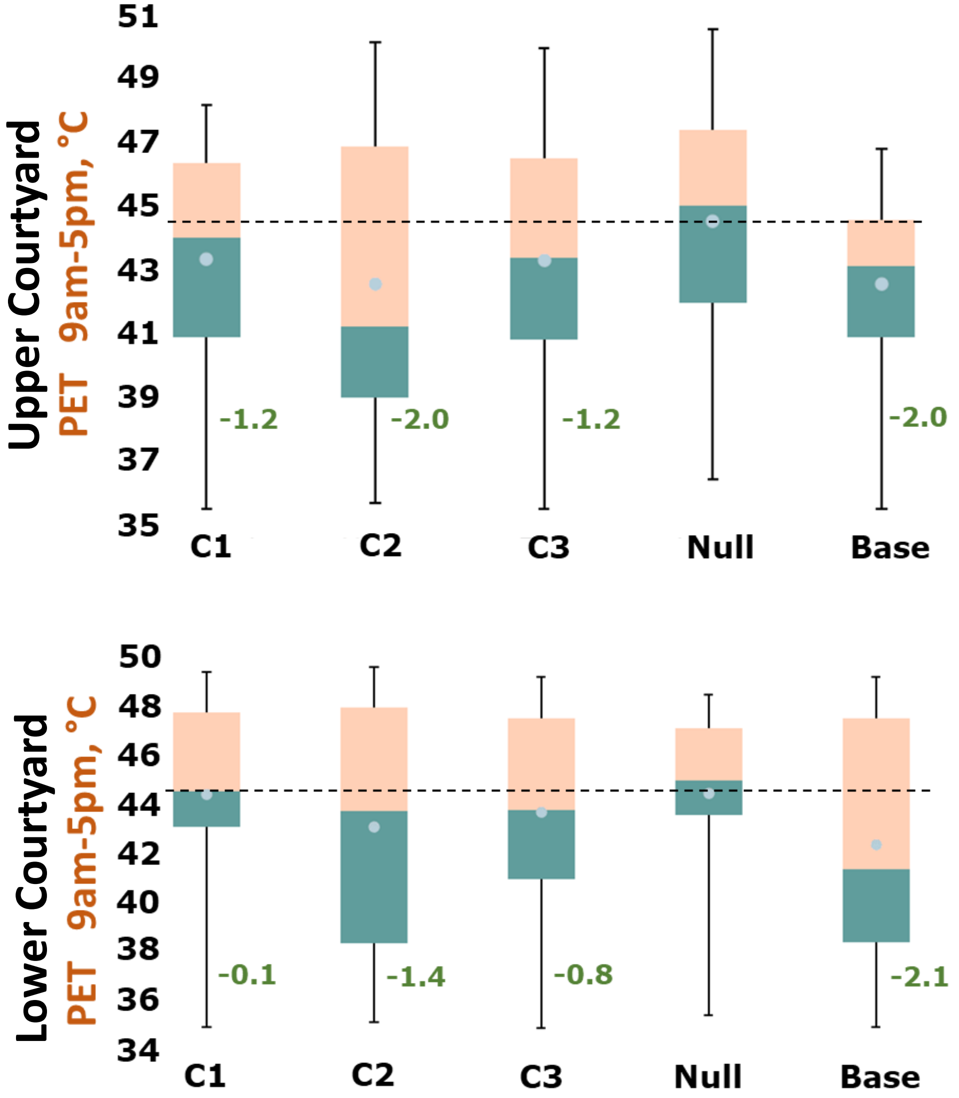
PARK

- Negligible air temperature reduction (<0.5°C) but **better mean radiant temperature reduction** (up to 2.8°C) between 9 am and 5 pm

OTC between 9 am to 5 pm

- **P1 showed highest ΔPET** (1.2°C) followed by P5 (0.6°C). Importance of **widespread shade and wind channelling** towards **PET reduction** becomes evident

Planting arrangement , PET (9am-5pm)



COURTYARDS

- Negligible air temperature reduction (<0.5°C) but **better mean radiant temperature reduction** (up to 5.2°C) between 9 am and 5 pm

OTC between 9 am to 5 pm

- **C2 showed highest ΔPET** (2°C and 1.4°C) followed by C3 (1.2°C and 0.8°C) for upper and lower courtyards respectively. Therefore, **middle plantation performs better** in courtyards as it facilitates **balanced shading pattern** over the courtyard area

Note: Avg. PET change is indicated in green colour text w.r.t. nullcase

- **Tree arrangement influences shade, wind speed and direction** on the site. Thus, **patterns parallel to wind or facilitating wind flow and widespread shade cool better while placing trees in wind corridors reduce thermal comfort during the daytime**

- Trees pattern only, without changing the trees cover percentage, has a limited impact on air temperature reduction. However, **selecting the proper tree arrangement at the appropriate location** could **increase OTC using fewer trees and occupying less area** inside the densely built residential neighbourhoods

- **Row of trees and clusters patterns** are the most optimal patterns in an **open area like the park**

- **Enhancing thermal comfort in the courtyards is a complex process. Trees' shape, location, and quantity** need to be carefully chosen **to balance sun and shade without blocking wind corridors.** Also, courtyards might probably be cooler during the day due to the narrow canyon that cuts some of the direct sun radiation, although the radiation reflected from the buildings might increase heat during the night, so **placing trees inside narrow canyons like courtyards need to be carefully investigated**

Subtropical tree species and Canopy cover scenarios

Subtropical tree species and Canopy cover scenarios

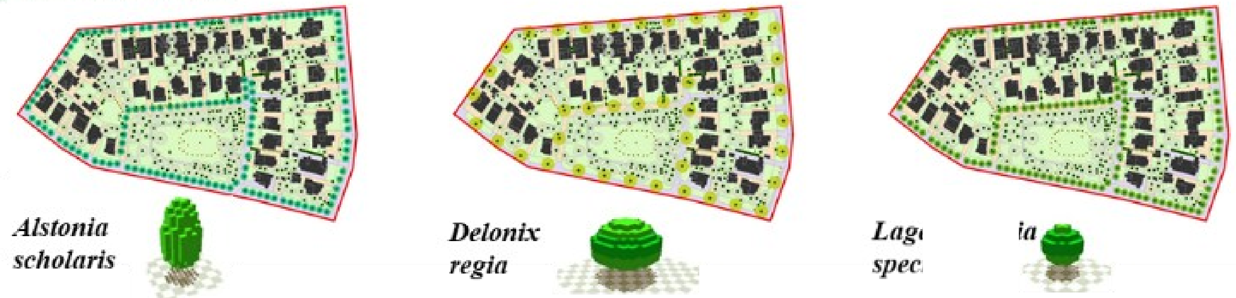
Status Quo

Null Scenario

No vegetation

Tree Species Scenarios

Street scenarios



Park scenarios

Garden scenarios

Canopy Cover Scenarios

Greening A scenario

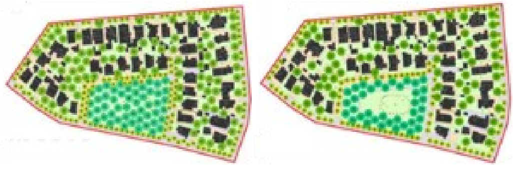
Cumulative scenario with the best performing tree species for each spatial typology (canopy cover same as status quo)

Greening B scenario

Greening A scenario + 5% canopy cover

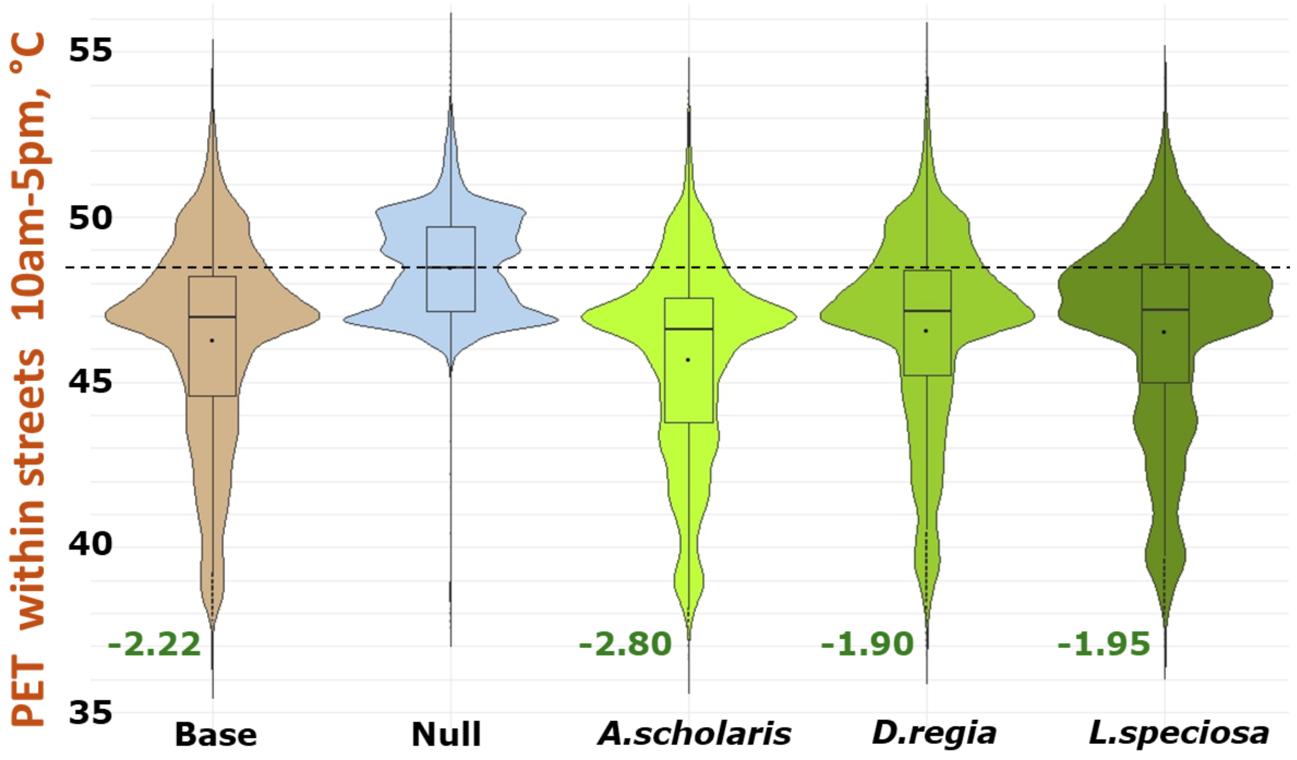
Greening C scenario

Greening A scenario - 5% canopy cover



(Without soil irrigation)

Subtropical tree species (Streets), PET (10am-5pm)

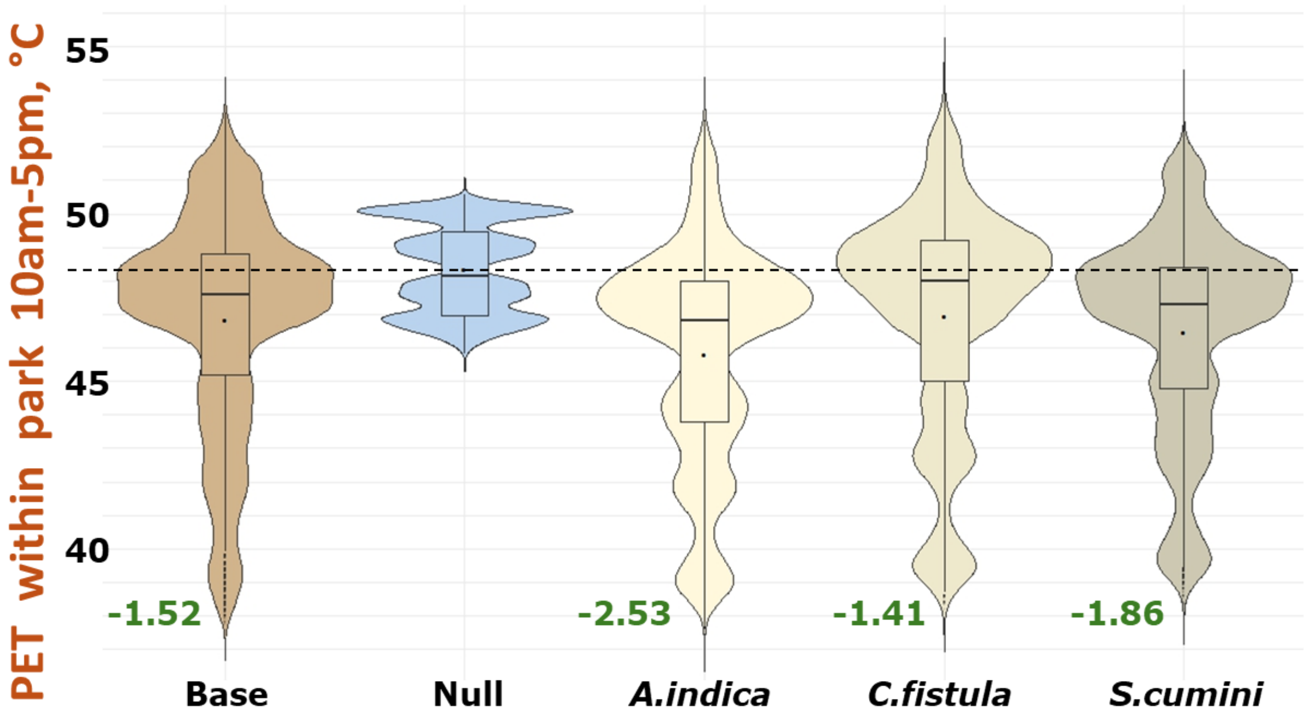


STREET TREES

- **Avg. PET is reduced by 2.80 ºC, 1.90 ºC and 1.95 ºC** for ***A.scholaris, D.regia,*** and ***L.speciosa***, respectively
- **PET reduction** within streets is also **influenced by the orientation and type of street** such as E-W streets displayed better PET reduction than N-S streets

Note: Avg. PET change is indicated in green colour text w.r.t. nullcase

Subtropical tree species (Park), PET (10am-5pm)

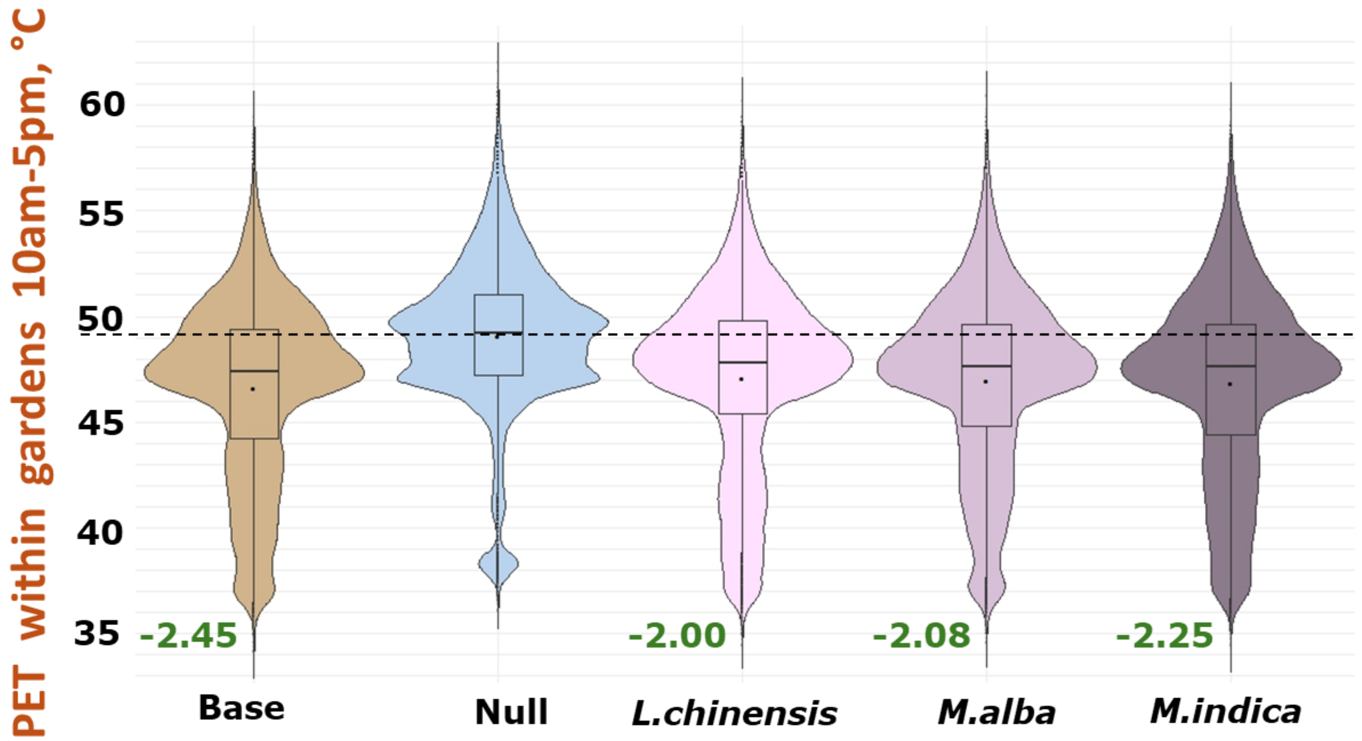


PARK TREES

- **Avg. PET is reduced by 2.53 °C, 1.41 °C and 1.86 °C** for ***A.indica, C.fistula*** and ***S.cumini***, respectively
- **Central open to sky lawn area** experiences **lowest PET reduction** and stays warmer than the other park sub-typologies because it consists mainly of **grass and shrubs which have lesser effective cooling potential than the trees**
- **Peripheral lawn areas under tree shade** indicate **slightly lower PET values** than the **pathway under tree shade** due to **denser shade of the tree clusters and underlying grass** which may influence cooling potential of trees better than the paved surfaces due to **higher potential for transpirational cooling**

Note: Avg. PET change is indicated in green colour text w.r.t. nullcase

Subtropical tree species (Gardens), PET (10am-5pm)

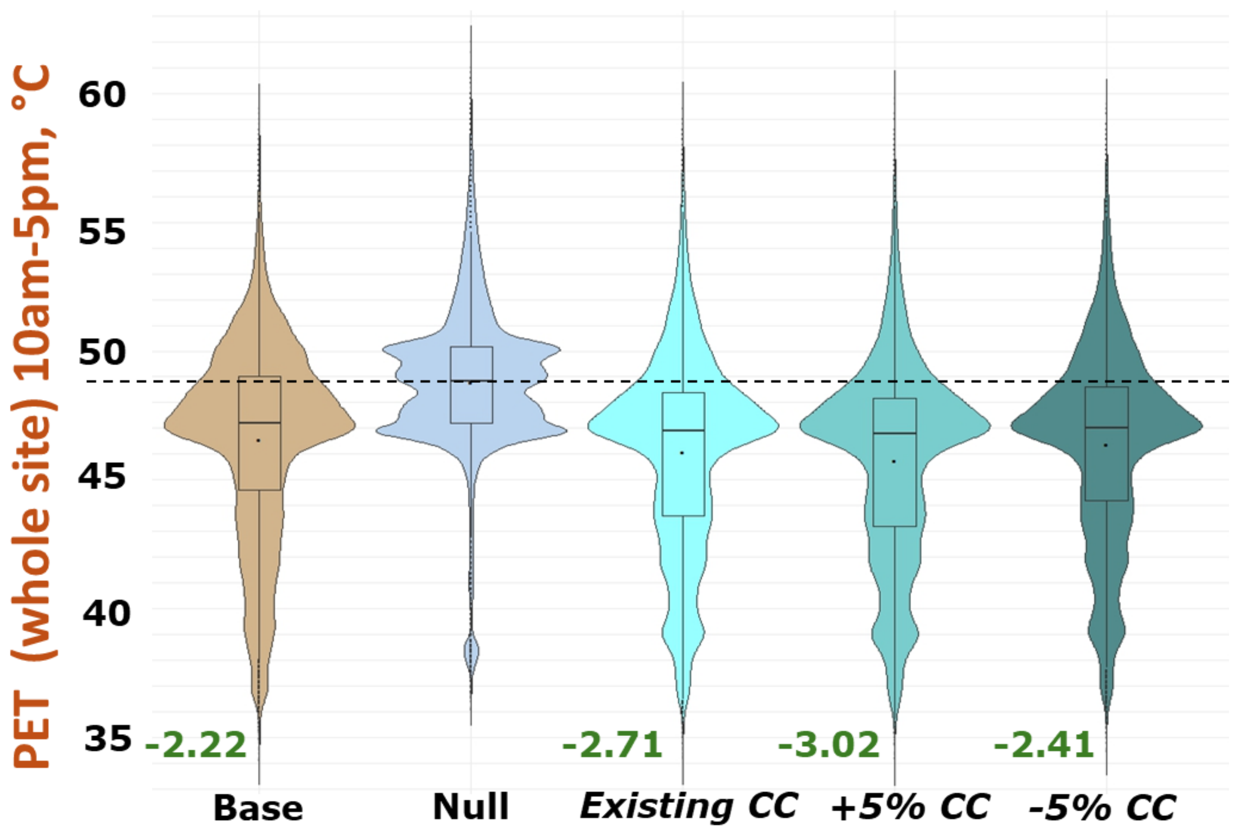


GARDEN TREES

- **Avg. PET is reduced by 2.00 ºC, 2.08 ºC and 2.25 ºC** for ***L.chinensis, M.alba*** and ***M.indica***, respectively
- All the three scenarios **reduce least PET in east facing frontyards** and **maximum in** the **north and south facing frontyards.** The **cooling variation** is influenced by **sky view factor, orientation, solar exposure and ventilation**
- **Gardens have certain areas cooler than park and streets** mostly in the **areas under building shade**
- **Interspecies cooling variation is least for the garden scenarios** as compared to street and park scenarios due to **tree traits as well as its built morphology**

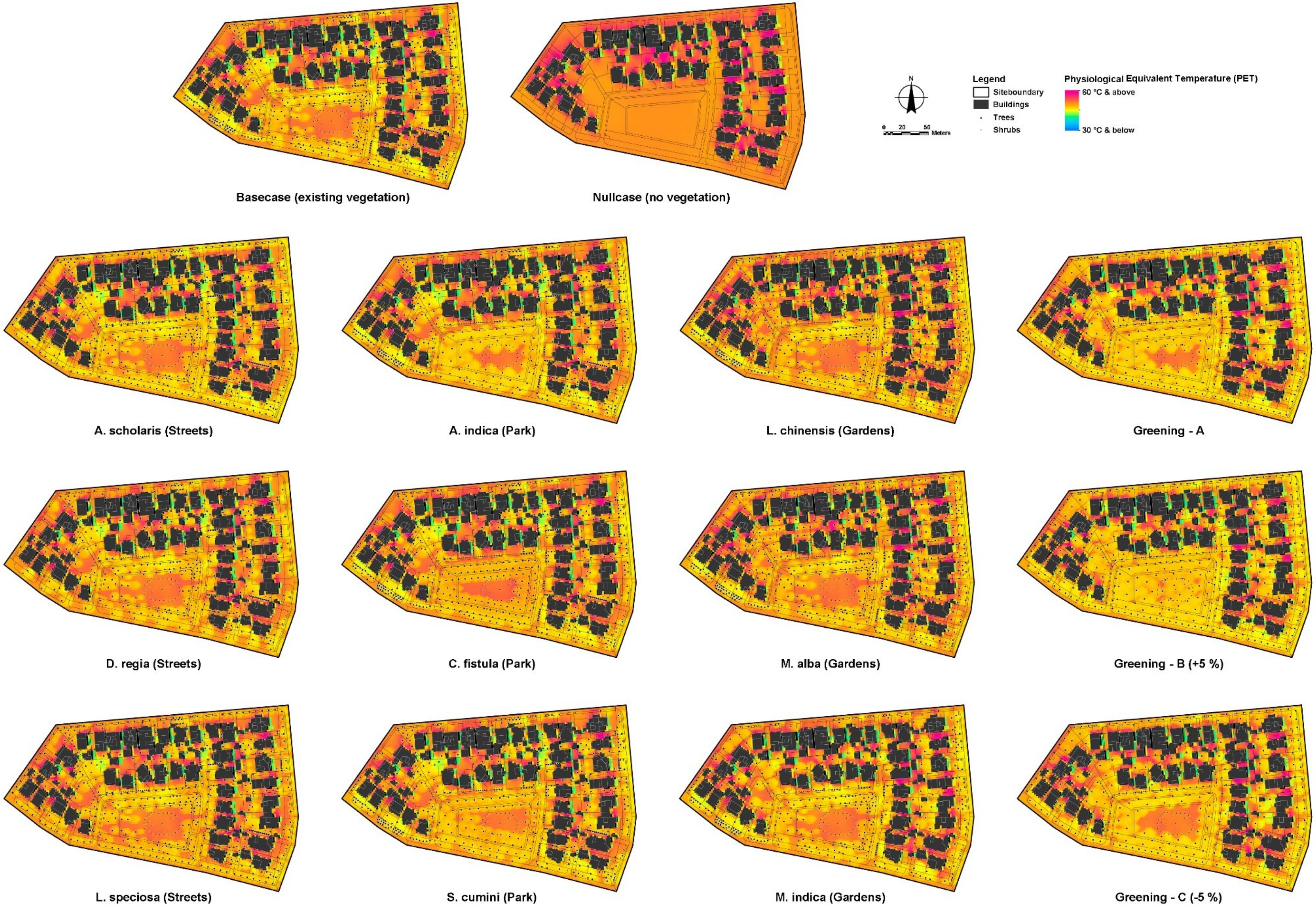
Note: Avg. PET change is indicated in green colour text w.r.t. nullcase

Canopy cover, PET (10am-5pm)



- **Avg. PET is reduced by** 2.71 ºC, 3.02 ºC and 2.41 ºC for ***Existing CC, +5% CC*** and ***-5% CC***, respectively
- There is a substantial decrease in higher PET values and a subsequent **shift** is seen **from extreme heat stress to strong and moderate heat stress** for all the three scenarios
- **Even in the comparison to basecase** (statusquo), all the three scenarios **indicate marginal cooling, even though 5% canopy cover was reduced in the 3rd CC scenarios**

Note: Avg. PET change is indicated in green colour text w.r.t. nullcase



Heat stress maps showing PET values for all the scenarios at 3pm (at 1.4m height)

- ***Alstonia scholaris, Azadirachta indica and Mangifera indica*** exhibit **maximum daytime cooling** in streets, park and gardens respectively, attributed primarily to **structural tree traits** like **canopy density and height**

- **Cooling efficacy** of trees **varies** within **different spatial setups** as well as due to **environmental factors like soil moisture, relative humidity, wind flow etc.**

- A particular species improving OTC at a particular urban setting is not necessarily best performing species for other urban settings. Moreover, small canopy trees were placed closer to each other than big canopy trees (to maintain same tree canopy cover in all scenarios) resulting in high PET values for latter. Therefore, it is **desirable to have closely placed trees for maximising shade,** bearing in mind **wind movement and enough sky view factor** for nighttime heat dissipation to avoid nocturnal UHI

- Results of the study are not a direct indication of best performing species but set a **precedent for urban planners, landscape designers or similar actors** for selecting tree species based on local site context to increase the efficiency and quality of the tree cover

- **Alternate adaptive strategies** (Artificial shading, behavioural adaptation measures) might be needed in peak heat summers due to **limited cooling efficacy capacity of trees in lowering extreme heat stress under heat and drought stress conditions**

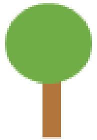
- **Cooling efficacy can be achieved by strategic choice of 'right tree' even under slightly lower canopy coverage.** Moreover, **OTC increases** with **canopy cover** and is **better** with **optimal tree species** i.e. **canopy quality** is more impactful than **canopy quantity**

Urban Green Infrastructure (UGI)type scenarios

UGI Type Scenarios

1_Basecase: **Existing situation (with soil irrigation)**

2_Nullcase: **No vegetation**



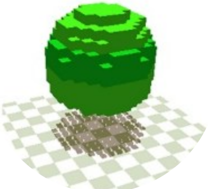
3_Trees scenario: **Combination of optimum subtropical tree species and planting arrangement**

Streets

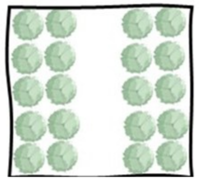
Alstonia Scholaris
(7x7x15 – DMO)

Group of two trees on single side of a street

Park

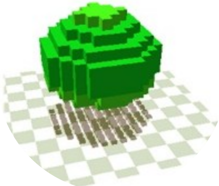


Azadirachta indica
(11x11x14 – DMR)

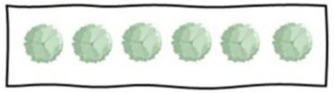


Row of trees parallel to wind

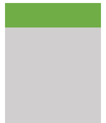
Courtyards /Gardens



Mangifera indica
(11x11x11 – DMR)



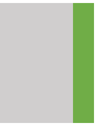
Middle plantation



4_Green roofs (GR): **Basecase + Green roofs**

Extensive green roof (20cm substrate, 2 LAI, 30cm plant height)

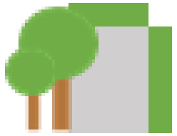
70-75% roof coverage in upwind direction



5_Green walls (GW): **Basecase + Green walls**

Climber (2 LAI, 30cm plant height)

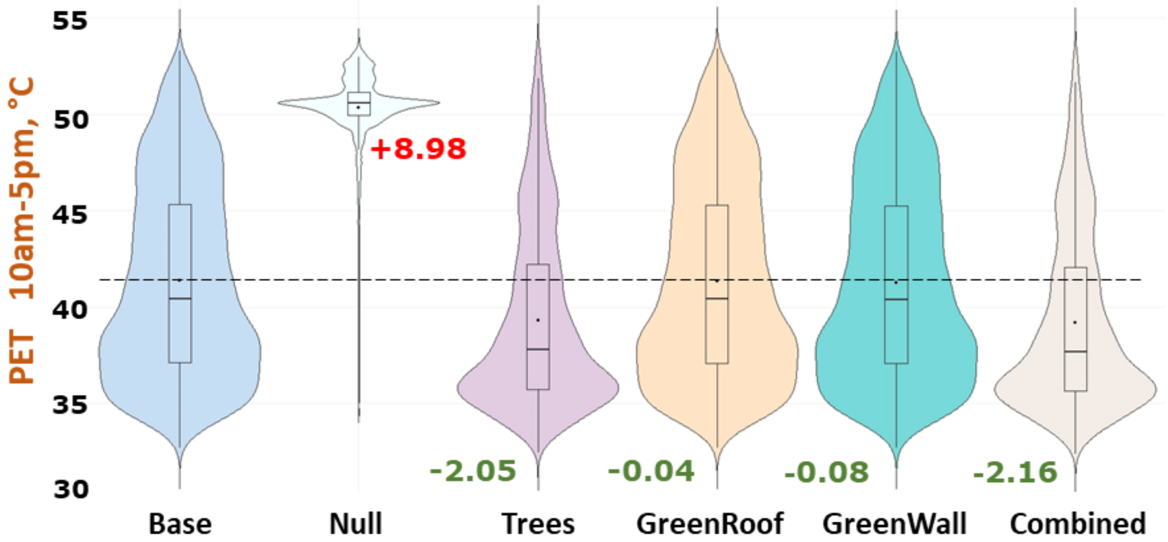
50-60% wall coverage on South, Southwest & West facades,
V. low SVF built canyons excluded



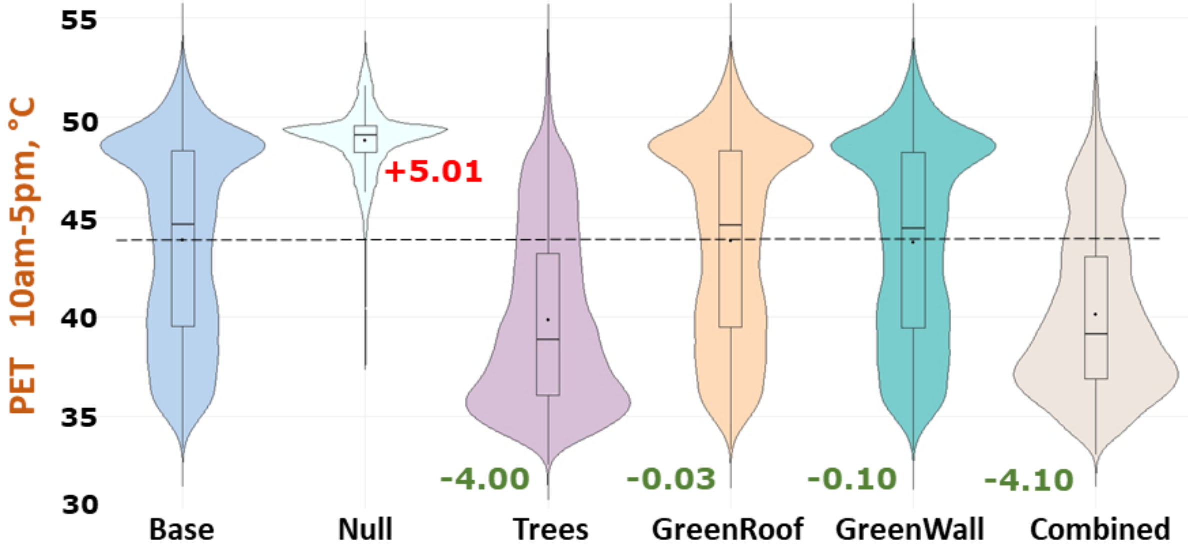
6_Combined: **Trees + Green Roofs + Green Walls**

UGI Types, PET (10am-5pm)

VV (Greener site) **Individual houses & private gardens**



AG (Less green site) **Block row houses & shared courtyards**



(with soil irrigation)

BaseCase

A **10% canopy cover difference** b/w both the sites influences **PET ranges (extreme vs moderate)** and **avg PET value (~3°C difference)**

Nullcase

Absence of vegetation results in **drastic difference** in avg PET (VV: ~9°C; AG: ~5°C) and PET ranges

Trees

Reduction in **extreme** (>42°C) and **high heat stress** (38-42°C) to moderate heat stress (34-38°C)

Green roof

Insignificant influence on average PET reduction (VV: 0.04°C; AG: 0.03°C)

Green wall

Slightly better avg. PET reduction than green roofs but still insignificant (VV: 0.08°C; AG: 0.10°C)

Combined

Role of **strategic UGI planning** is evident in avg. PET reduction (VV: 2.16°C; AG: 4.10°C). **Combined impact of green roofs and green walls stays minimal** (VV: 0.10°C; AG: 0.11°C)

Note: Avg. PET change is indicated in red and green colour text w.r.t. basecase

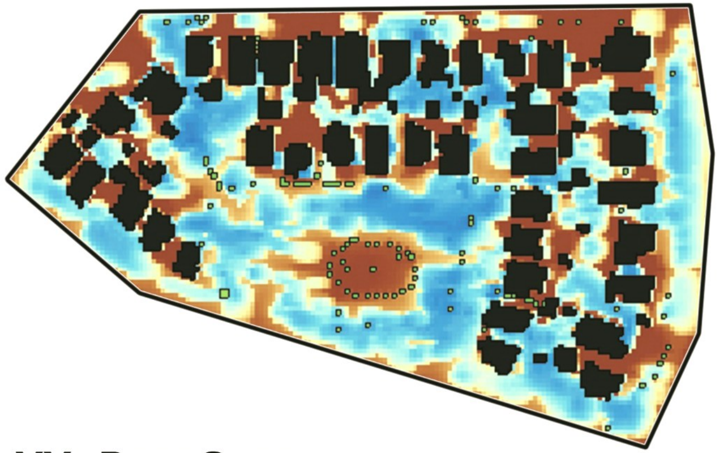
Cooling Intensity (CI) (ºC): Cooling potential w.r.t. basecase at peak heat stress hour and during occupancy period

	VV_BC	VV_Null		VV_Trees		VV_GR		VV_GW		VV_All	
3 pm	42.57	51.54	8.96 **(+21%)**	40.32	-2.26 **(-5.30%)**	42.54	**-0.04**	42.46	**-0.12**	40.17	-2.41 **(-5.70%)**
10 am – 5 pm	41.36	50.34	8.98 **(+21.70%)**	39.31	-2.05 **(-5%)**	41.33	**-0.04**	41.28	**-0.08**	39.20	-2.16 **(-5.20%)**
	AG_BC	**AG_Null**		**AG_Trees**		**AG_GR**		**AG_GW**		**AG_All**	
3 pm	45.89	50.71	4.82 **(+10.50%)**	41.77	-4.13 **(-8.9%)**	45.78	**-0.02**	45.78	**-0.11**	41.66	-4.24 **(-9.20%)**
10 am – 5 pm	43.83	48.85	5.01 **(+11.40%)**	39.84	-4.00 **(-9.10%)**	43.81	**-0.03**	43.73	**-0.10**	39.73	-4.10 **(-9.40%)**

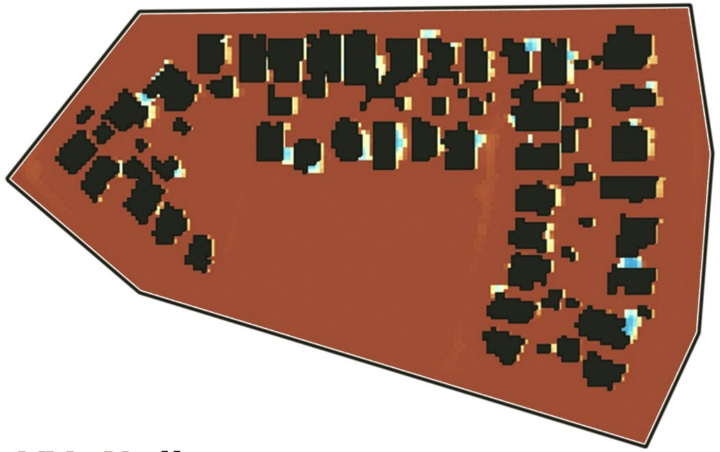
Avg. PET values and cooling intensity for each scenario w.r.t basecase
(+ve: Heating; -ve: Cooling)

- **Cooling intensity of Trees scenarios is best: CI of 5%** is achieved for **VV site** with a minimal increase of **0.74% green cover** and **CI of 9%** is achieved for **AG site** with an increase of **5.0% green cover**
- **Cooling intensity of green roofs and green walls** is **minimal** (At 3pm: GR: VV 0.11-0.50ºC, AG- upto 0.16ºC and GW: VV- 0.30-1.60ºC, AG- upto 0.30-3.0ºC)
- **Green roofs on 3-4m high buildings** located in **upwind and unrestricted wind direction** perform **better**. However, the **cooling area** is restricted to **2-4m distance** from the buildings. **Lack of wind** can even cause **heating in certain canyons**
- In case of **Green walls**, cooling extends upto **2-4m distance** and seems to be influenced by **wind flow and high SVF values**. A consistent impact of **sky view factor, building orientation and green coverage** was, however, **not established**. Besides, the **impact of building shade** is **more prominent** than the cooling from green walls

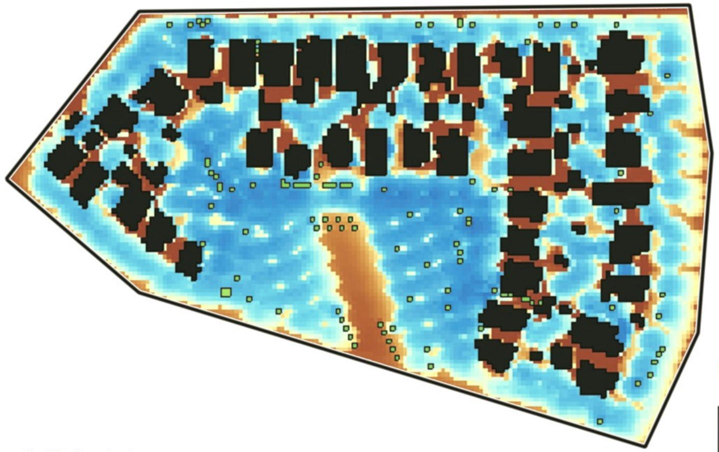
PET (3pm) VV (Greener site) Individual houses & private gardens



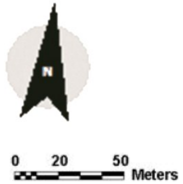
VV_BaseCase

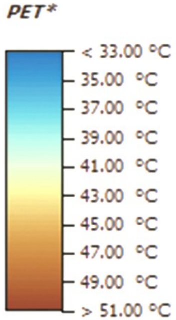


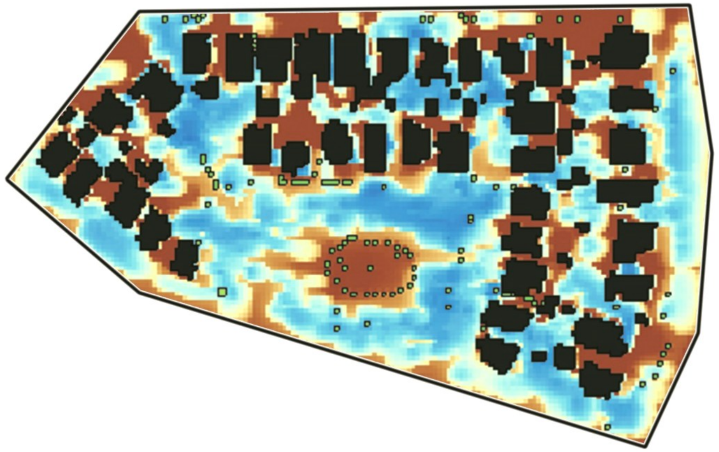
VV_Null



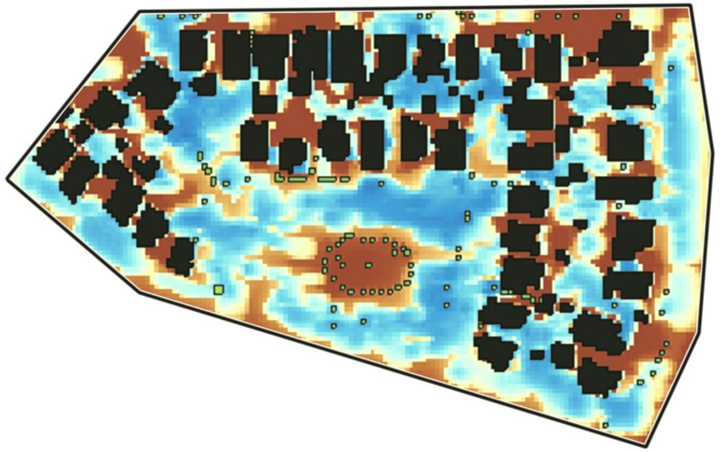
VV_Trees



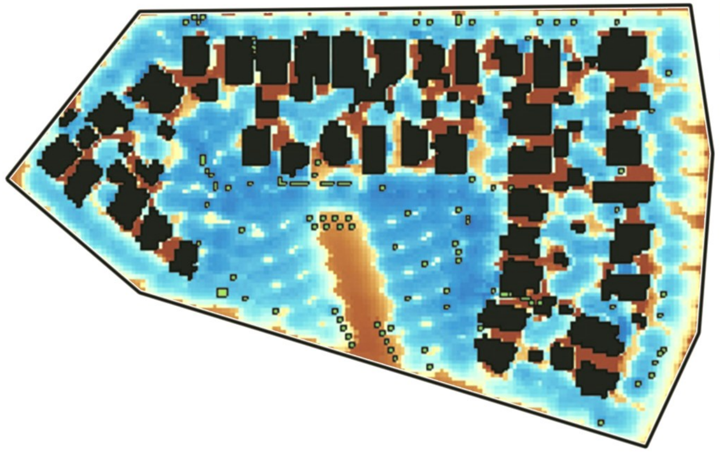




VV_GreenRoof

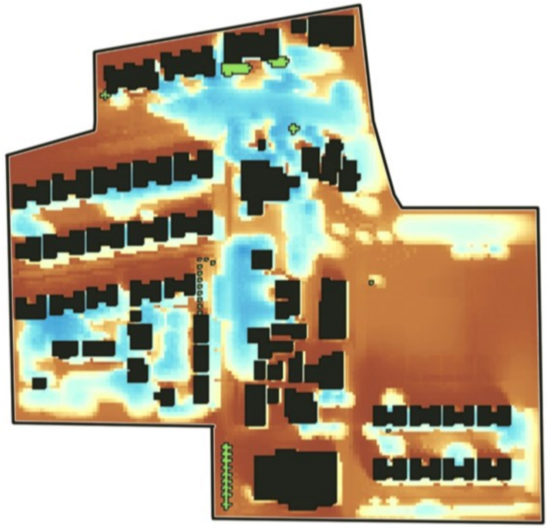


VV_GreenWall

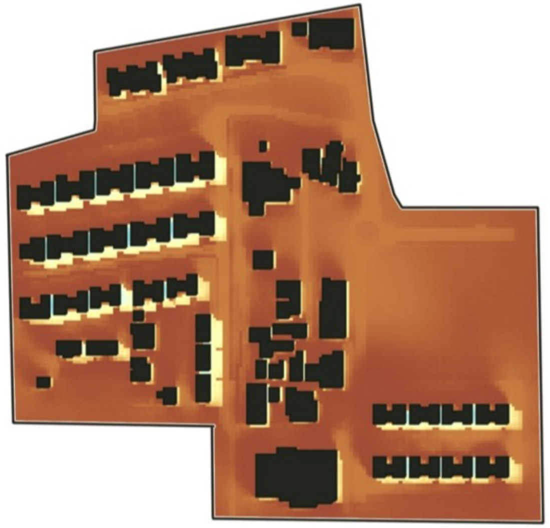


VV_Combined

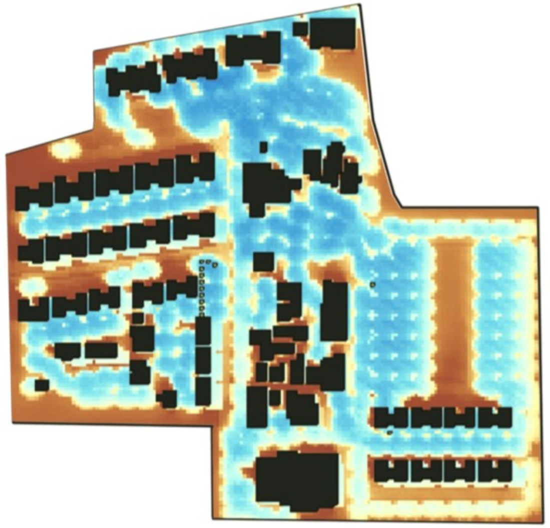
PET (3pm) AG (Less green site) Block row houses & shared courtyards



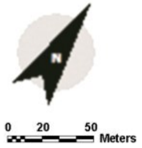
AG_BaseCase

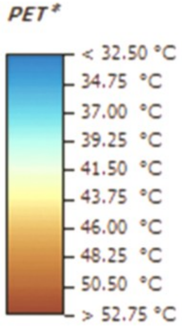


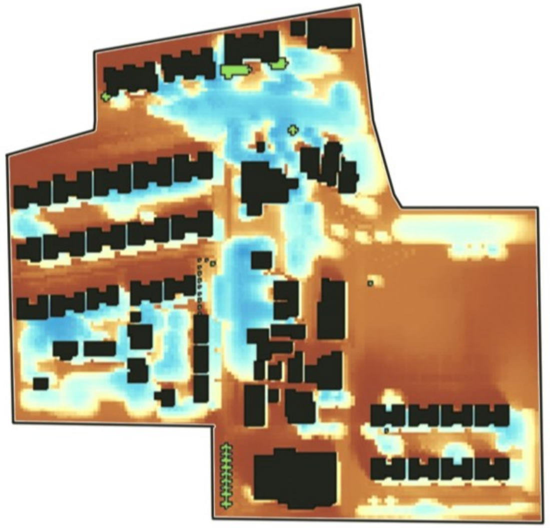
AG_Null



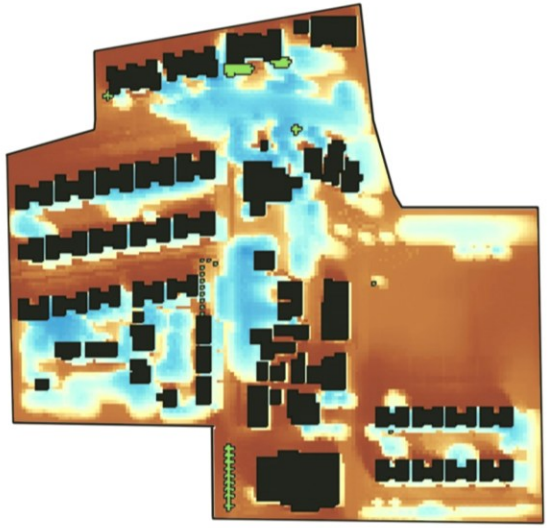
AG_Trees



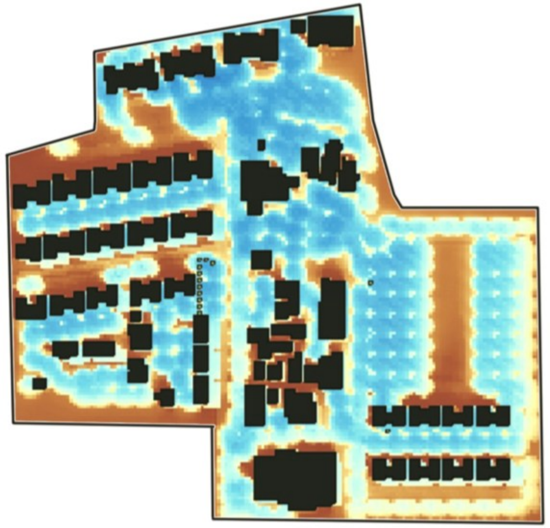




AG_GreenRoof



AG_GreenWall



AG_Combined

- **Trees** have **highest cooling impact** due to increased evaporative cooling & shade which is further enhanced by **soil irrigation** and **strategic planning** in terms of **tree species type, planting arrangement and canopy cover**

- **Green roofs (extensive)**:
  - **Negligible cooling impact** irrespective of the urban form but slightly influenced by **wind flow and building height**
  - **No evident influence of coverage area**
  - Need to **design buildings** that can withstand structural load of **intensive green roofs** from early planning stages

- **Green walls (climber)**:
  - **Better than green roofs** but mostly confined close to facades only
  - **Wind flow, position of sun, SVF and building orientation** increases cooling sometimes but results are not consistent
  - **No evident and consistent influence of coverage area**

- Overall, **urban morphology** contributes to **heat stress differences** on the sites but **does not have major impact** on **performance of greening strategies** esp. for *pedestrian OTC*. However, the **built forms channelizing wind flow** would **benefit more from building greening**

- Moreover, the **sites with low height buildings and private gardens** like Vasant Vihar can benefit more with close vicinity to green roofs and green walls

- **Performance of building greening** is **poorer in case of real neighbourhoods** unlike idealised neighbourhoods due to the hyper-local influences

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