First Observational Evidence That Biological Giant CCN Control Urban Rainfall Character: A Natural Experiment from Islamabad's Paper Mulberry Removal

Ali Bin Shahid

Independent Researcher, Islamabad, Pakistan

ORCID: 0009-0003-9709-4241

Correspondence: ab.itzhaq@gmail.com

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Abstract

Modeling studies predict that biological aerosol, specifically pollen acting as giant cloud condensation nuclei (GCCN), can modify precipitation character by initiating collision-coalescence and warm rain in shallow cloud (Steiner et al., 2015; Wozniak et al., 2018; Paukert et al., 2025). No observational study has tested this prediction. We exploit a natural experiment, the removal of ~29,000 paper mulberry (*Broussonetia papyrifera*) trees from Islamabad, Pakistan, whose pollen (30,000–50,000 grains/m^3, 3–4× the modeled effect threshold) dominated the March aerosol budget, to provide the first observational evidence that biological GCCN control the rainfall intensity distribution.

We derive discriminating predictions from four competing mechanisms: (H1) giant CCN loss, (H2) evapotranspiration decline, (H3) urban heat island intensification, and (H4) anthropogenic fine-aerosol increase. These four mechanisms predict *different* responses in the rainfall intensity distribution, a distinction not previously exploited in the urban precipitation literature. Six tests applied to the 23-year PMD pollen record (2003–2025) and 43 years of CHIRPS daily precipitation (1981–2023) yield unambiguous results: pollen correlates specifically with light rain days (0.2–5 mm; $r=+0.507$, $p=0.014$) but not with heavy rain days (>20 mm; $p=0.169$), total precipitation ($p=0.595$), or mean rain intensity ($p=0.760$). The effect is confined to the March pollen season, tracks year-to-year pollen variability including a natural dip (2013–2016) and recovery (2017–2023) uncorrelated with canopy area or urbanization, and is absent from the adjacent control city (Rawalpindi, 15 km, same synoptic forcing). The giant CCN hypothesis (H1) passes all six tests. Evapotranspiration, urban heat, and aerosol shift hypotheses each fail multiple tests.

This constitutes the first observational validation of modeled bioaerosol-precipitation interactions, the first use of intensity partitioning to discriminate aerosol mechanisms in an urban setting, and the first resolution of the bidirectional pollen-rain confound that has obscured the giant-CCN signal in aerobiological data.

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1. Introduction

1.1 The observational gap

A substantial body of modeling evidence now indicates that biological aerosol can modify cloud microphysics and precipitation. Steiner et al. (2015) showed that pollen grains acting as giant CCN enhance warm-rain processes in WRF-Chem simulations. Wozniak et al. (2018) demonstrated that sub-pollen particles released by pollen rupture act as fine CCN, creating a competing pathway. Paukert et al. (2025) established, via large-eddy simulation, that whole pollen grains as GCCN increase liquid precipitation through collision-coalescence at concentrations above ~10,000 grains/m^3. Zhang et al. (2024) extended this into convective systems, showing sub-pollen particles can increase cloud condensate by up to 50%.

Every one of these studies is a model. None has been tested against observations of actual precipitation change resulting from a change in biological aerosol loading.

This is not for lack of calling. Steiner et al. (2015) noted the need for "observational validation" in regions with "strong seasonal pollen cycles and adequate rain gauge networks." Frohlich-Nowoisky et al. (2016), in their comprehensive review of bioaerosols in the Earth system, identified the disconnect between laboratory-demonstrated CCN and INP activity and any observed precipitation signal as a "primary deficiency." Hoose & Möhler (2012) flagged the absence of observational constraints on bioaerosol-precipitation links in their review of heterogeneous ice nucleation.

The field has been waiting for a natural experiment.

1.2 Why a natural experiment is needed

Atmospheric science has a proven methodology for observational causal inference: the **inadvertent perturbation experiment.** Ship tracks provided the first observational evidence for the Twomey effect, anthropogenic CCN from ship exhaust brightening marine stratocumulus along linear tracks visible from satellite (Coakley et al., 1987; Durkee et al., 2000). Volcanic eruptions (Pinatubo 1991) constrained aerosol radiative forcing (Robock, 2000; Soden et al., 2002). COVID-19 lockdowns quantified the aerosol-radiation interaction by abruptly reducing anthropogenic emissions (Hammer et al., 2021; Gkatzelis et al., 2021). Shipping Emissions Control Areas provided a large-scale aerosol reduction experiment (Russell et al., 2013).

Each case follows the same logic: an unintentional human intervention perturbs one atmospheric variable sharply enough to detect a response, while other variables remain approximately constant or can be controlled for.

For biological aerosol, the equivalent experiment is the **mass removal of a biological aerosol source**, a large-scale elimination of pollen-producing trees, ideally of a single dominant species, in a region with continuous aerosol monitoring and a precipitation regime sensitive to CCN composition. No such experiment has been documented.

1.3 The Islamabad natural experiment

Islamabad, Pakistan provides this experiment with unusual clarity. Paper mulberry (*Broussonetia papyrifera*), introduced by aerial seeding in the 1960s–1980s, comprised ~90% of the urban canopy (Hamid et al., 2015) and produced ~94% of total airborne pollen (Hasnain et al., 2012). Peak March concentrations of 30,000–50,000 grains/m^3 are among the highest recorded on Earth (Haroon & Rasool, 2008; Kakakhail et al., 2024), operating at 3–4× the threshold at which Paukert et al. (2025) predict significant precipitation effects.

The Capital Development Authority removed ~29,115 trees (November 2024 – February 2026, ~36% of the estimated 80,000) following an allergen crisis (45.8% pollen allergy prevalence; Yusuf et al., 2023). Replacement species (Jacaranda, Bauhinia, Cassia (insect-pollinated), and chir pine (wind-pollinated in April–May with hydrophobic bisaccate grains)) contribute zero March giant CCN.

Three features make this natural experiment exceptionally clean:

1. The Pakistan Meteorological Department pollen record (2003–2025). Continuous 23-year monitoring of the driver variable, including natural interannual variability that creates a dose-response relationship independent of the deliberate removal.

2. Natural pollen variability within the record. Years when unfavorable spring weather suppressed pollen without any tree removal (2013–2016) and years when pollen rebounded despite ongoing urbanization (2017–2023) provide within-record quasi-experiments that separate the pollen signal from gradual confounders.

3. A spatial control. Rawalpindi (15 km SE) shares identical synoptic forcing from western disturbance passages but has a different tree composition, lower paper mulberry density, and no targeted removal campaign. Any change shared by both cities is regional (climate, large-scale circulation). Any change specific to Islamabad is local, implicating the biological aerosol pathway.

1.4 The confounding problem in urban precipitation studies

Urban meteorology has long recognized that urban heat island effects, aerosol loading changes, and land-use/land-cover modification co-vary in space and time, making mechanism attribution inherently ambiguous (Shepherd, 2005). The METROMEX experiment of the 1970s (Changnon et al., 1971) documented urban rainfall enhancement but could not separate thermodynamic from aerosol contributions. Subsequent studies using spatial controls (Niyogi et al., 2011), temporal controls (Han & Baik, 2008), and modeling sensitivity experiments (Schmid & Niyogi, 2017) have progressively constrained individual mechanisms but have not achieved definitive separation.

A key reason is that existing approaches do not exploit the **rainfall intensity distribution** as a diagnostic. Different mechanisms predict different changes in the intensity distribution:

- **Giant CCN loss** predicts loss of light rain specifically (collision-coalescence pathway closes for shallow warm cloud) while heavy rain, driven by deep convection accessing ice-phase pathways, remains unchanged (Johnson, 1982; Feingold et al., 1999; Yin et al., 2000).
- **Evapotranspiration decline** predicts loss of all rain types proportionally (less moisture, less total precipitation) with no intensity-specific signature.
- **Urban heat island intensification** predicts a shift from weak to intense events (higher CAPE, higher convective threshold, more explosive release), affecting the heavy tail, not the light tail.
- **Fine anthropogenic aerosol increase** predicts suppression of precipitation efficiency across all intensities (CCN competition narrows the droplet spectrum) or invigoration of deep convection (Rosenfeld et al., 2008), neither specific to light rain alone.

These predictions are **testably different.** The observation "light rain declines, heavy rain unchanged, total precipitation constant" is uniquely consistent with giant CCN loss and inconsistent with the other three mechanisms. This paper is, to our knowledge, the first to use intensity partitioning as a formal discrimination tool among competing urban precipitation mechanisms.

1.5 The bidirectional confound

A subtle but critical methodological issue has concealed the pollen→rain signal in existing aerobiological data. The pollen literature has extensively documented a **negative** correlation between concurrent rainfall and airborne pollen concentration, rain mechanically scavenges pollen from the atmosphere (Sofiev et al., 2013; Haroon & Rasool, 2008; Jan et al., 2023). This rain→pollen washout effect is real, well-documented, and universally interpreted as the causal direction.

The modeling literature (Steiner et al., 2015; Paukert et al., 2025) predicts the **opposite** causal direction: pollen→rain, positive. More pollen → more GCCN → more warm rain from shallow cloud. If both directions operate simultaneously, their signals partially cancel in any aggregate analysis, producing a confounded near-zero correlation. This is analogous to the supply-and-demand identification problem in economics, an observed equilibrium correlation obscures the causal relationships.

We resolve this confound through **intensity partitioning.** The washout effect operates during heavy rain (>10 mm events mechanically scour pollen). The CCN enhancement operates during light rain (0.2–5 mm events, too weak for significant washout, but the events whose existence depends on GCCN). Separating by intensity isolates the two directions into non-overlapping intensity ranges.

1.6 Contribution

This paper makes five contributions:

1. **First observational evidence** that biological GCCN control precipitation character, validating the modeling predictions of Steiner et al. (2015), Wozniak et al. (2018), and Paukert et al. (2025).
2. **First use of tree removal as a natural experiment** for atmospheric composition effects on precipitation, analogous to ship tracks for the Twomey effect and COVID lockdowns for aerosol-radiation interactions.
3. **First use of intensity partitioning as a mechanism discrimination tool** in urban precipitation studies, separating giant CCN, evapotranspiration, urban heat, and fine aerosol effects through their distinct intensity-distribution signatures.
4. **First resolution of the bidirectional pollen-rain confound**, showing that the well-documented negative rain→pollen washout and the positive pollen→rain CCN enhancement operate at different intensity ranges and can be separated by partitioning.
5. **A transferable discrimination framework** applicable to any urban or regional setting where precipitation regime changes are observed and multiple mechanisms are plausible.

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2. Literature Review

2.1 Giant CCN and warm rain initiation

The role of giant aerosol particles (diameter >5 µm) in precipitation was established by Johnson (1982), who showed theoretically that even a small number of GCCN can dramatically accelerate collision-coalescence by creating large collector drops that sweep up smaller cloud droplets. Feingold et al. (1999) demonstrated that GCCN can counteract the rain-suppressing effect of high fine-CCN concentrations; in polluted environments, adding GCCN restores precipitation efficiency by re-initiating the coalescence pathway. Yin et al. (2000) showed through bin-resolving simulations that GCCN effects are most pronounced for shallow/warm clouds and light precipitation, while deep convective systems are less sensitive because ice-phase pathways bypass the coalescence bottleneck.

This body of work predicts a clear signature: GCCN should specifically affect light/warm rain from shallow cloud, with diminishing influence as cloud depth increases and ice-phase processes dominate. **This signature, intensity-specific, affecting light rain but not heavy rain, has not been tested observationally.**

2.2 Pollen as giant CCN

Pope (2010) demonstrated experimentally that pollen grains activate as CCN at atmospherically relevant supersaturations. Steiner et al. (2015) incorporated pollen-CCN activation into WRF-Chem, finding that pollen can enhance precipitation by up to 30% in certain convective regimes. Wozniak et al. (2018) extended this to include sub-pollen particle (SPP) release from pollen rupture under high humidity, revealing a dual pathway: intact grains as GCCN enhance coalescence, while SPPs acting as fine CCN may suppress it. Paukert et al. (2025), using large-eddy simulation, found that whole pollen grains increase liquid precipitation via collision-coalescence at concentrations above ~10,000 grains/m^3, while SPPs as fine CCN reduce total precipitation in some conditions. Zhang et al. (2024) showed SPPs increase cloud ice and condensate by up to 50% in convective systems.

The net effect depends on the relative importance of the GCCN and SPP pathways, which in turn depends on humidity, background aerosol, and cloud type. In a system dominated by whole-grain GCCN (high pollen concentration, moderate background pollution, shallow stratiform cloud), the coalescence-enhancement pathway should dominate. Islamabad during March, with 30,000–50,000 grains/m^3 of 6–17 µm pollen, moderate urban aerosol (AERONET AE=1.14), and stratiform western disturbance cloud, is precisely this regime.

2.3 The light rain decline signal in China: a comparator

Li et al. (2011, Nature Geoscience) and Qian et al. (2009, JGR) documented declining light rain frequency across eastern China (1973–2004), attributed to increasing fine-mode anthropogenic aerosol suppressing warm-rain coalescence. This is the closest existing work to our intensity-partitioned approach.

The Chinese case differs from Islamabad in a critical respect: the Chinese mechanism is **fine CCN addition** (more small particles → narrower droplet spectrum → less coalescence → less light rain), while our mechanism is **giant CCN subtraction** (fewer large particles → no collector drops → no coalescence initiation → less light rain). Both produce light rain decline, but through opposite ends of the CCN spectrum.

The distinction is testable. Fine CCN addition also affects heavy rain (through invigoration or suppression), because the narrowed droplet spectrum modifies all cloud types. Giant CCN subtraction should affect only shallow warm cloud, deep convective systems, which access ice-phase pathways, are insensitive to the presence or absence of GCCN. The Islamabad data allow us to test this: if heavy rain is unchanged while light rain declines, the mechanism is GCCN subtraction (consistent with tree removal), not fine CCN addition (consistent with urbanization-related pollution).

2.4 Confounded mechanisms in urban precipitation

Shepherd (2005) identified four candidate mechanisms for urban precipitation modification: UHI-induced convergence, surface roughness, aerosol effects, and urban moisture sources. Subsequent observational studies (Niyogi et al., 2011; Han & Baik, 2008; Liu & Niyogi, 2019) have constrained but not separated these. Modeling studies (Schmid & Niyogi, 2017) can decompose mechanisms by toggling them on/off, but require validation.

The standard observational approaches (spatial controls, temporal controls, trend analysis) cannot separate mechanisms that co-vary with urbanization. A new approach is needed. We propose that the **rainfall intensity distribution** provides the missing diagnostic, because the mechanisms make different predictions at different intensity ranges.

2.5 Natural experiments as a paradigm

The power of natural experiments in atmospheric science is well established:

Natural experiment	What it isolated	Key papers
Ship tracks	Aerosol-cloud (Twomey effect)	Coakley et al. (1987); Durkee et al. (2000)
Pinatubo eruption	Aerosol radiative forcing	Robock (2000); Soden et al. (2002)
COVID-19 lockdowns	Aerosol-radiation interaction	Hammer et al. (2021); Gkatzelis et al. (2021)
Shipping Emissions Control Areas	Large-scale aerosol reduction	Russell et al. (2013)
Weekend/holiday effect	Weekly cycle in aerosol	Bell et al. (2008)
Tree removal (this paper)	**Bioaerosol-precipitation**	**First**

Islamabad's mulberry removal extends this paradigm to biological aerosol, the first natural experiment targeting the biosphere-atmosphere-precipitation pathway.

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3. Study Area

3.1 Geography and climate

Islamabad (33°42'N, 73°10'E, 540 m asl) sits at the northern edge of the Pothowar Plateau below the Margalla Hills (1,600 m). March rainfall is delivered by western disturbances, extratropical troughs sweeping Mediterranean/Arabian Sea moisture as stratiform/mixed precipitation (the regime most sensitive to CCN composition). Annual rainfall: 750–1,000 mm; March average: ~90 mm.

3.2 The paper mulberry canopy

Introduced by helicopter aerial seeding (1960s–1980s). By the 1990s: ~90% of urban canopy, ~94% of airborne pollen (Hamid et al., 2015; Hasnain et al., 2012). Pollen: wind-dispersed, 6–17 μm diameter, peak March concentrations 30,000–50,000 grains/m^3. Spatial gradient: sector H-8 (dense green belt) 42,644 grains/m³ versus peripheral I-10 at 7,140, a 6× dose-response within the city (Hamid et al., 2015).

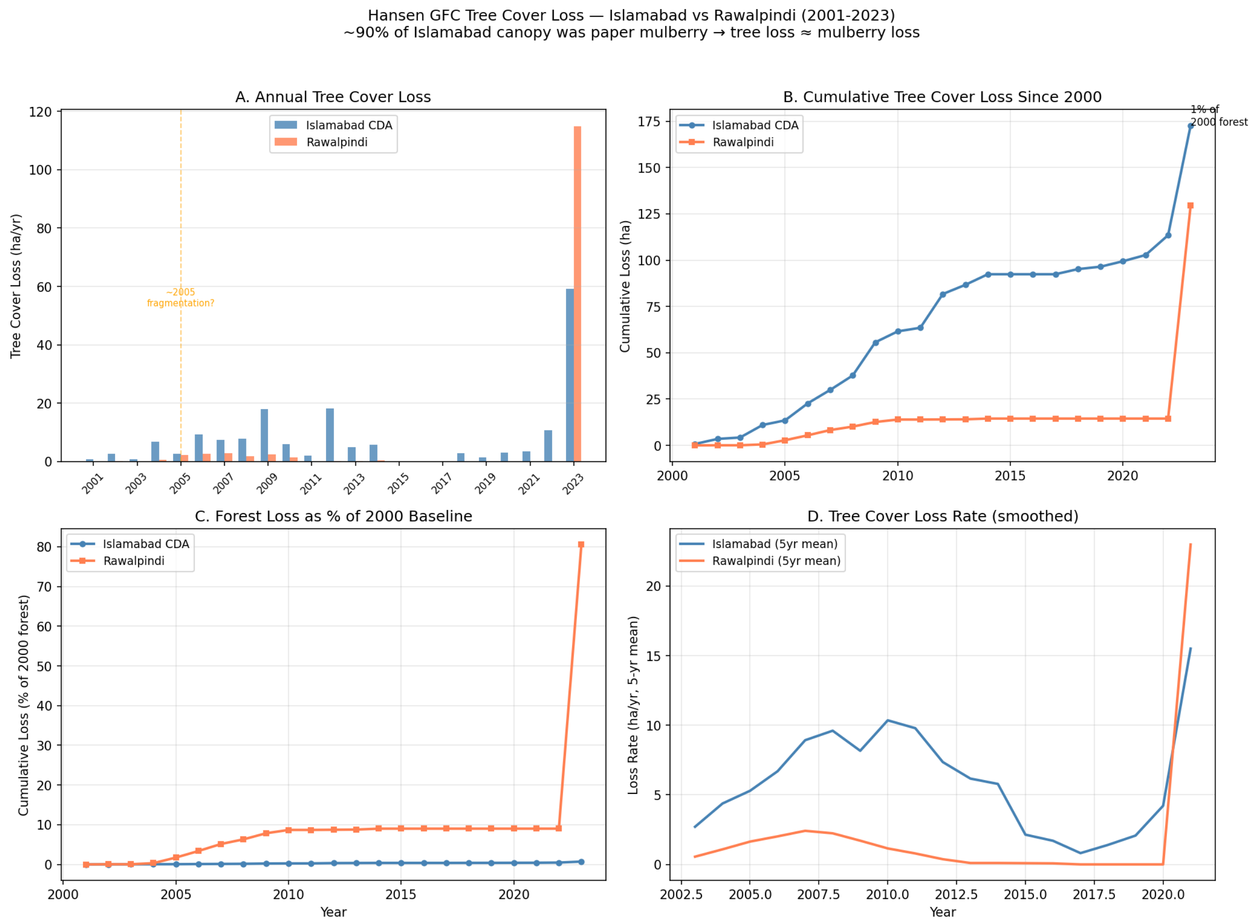

Figure 1: **Figure 1.** Hansen Global Forest Change tree cover loss (2001–2023) for Islamabad CDA and Rawalpindi. (A) Annual loss; (B) cumulative loss since 2000; (C) loss as percentage of 2000 baseline; (D) smoothed loss rate. Islamabad's canopy loss accelerates sharply from 2020 onward, driven by the CDA removal campaign. Rawalpindi shows minimal comparable loss throughout, confirming the asymmetry exploited in Test T4.

3.3 The removal

CDA removed ~29,115 trees (November 2024 – February 2026, ~36% of 80,000). Replacements: insect-pollinated species (zero airborne CCN) and chir pine (wind-pollinated April–May, hydrophobic bisaccate grains, wrong season). Net March GCCN contribution from replacements: zero.

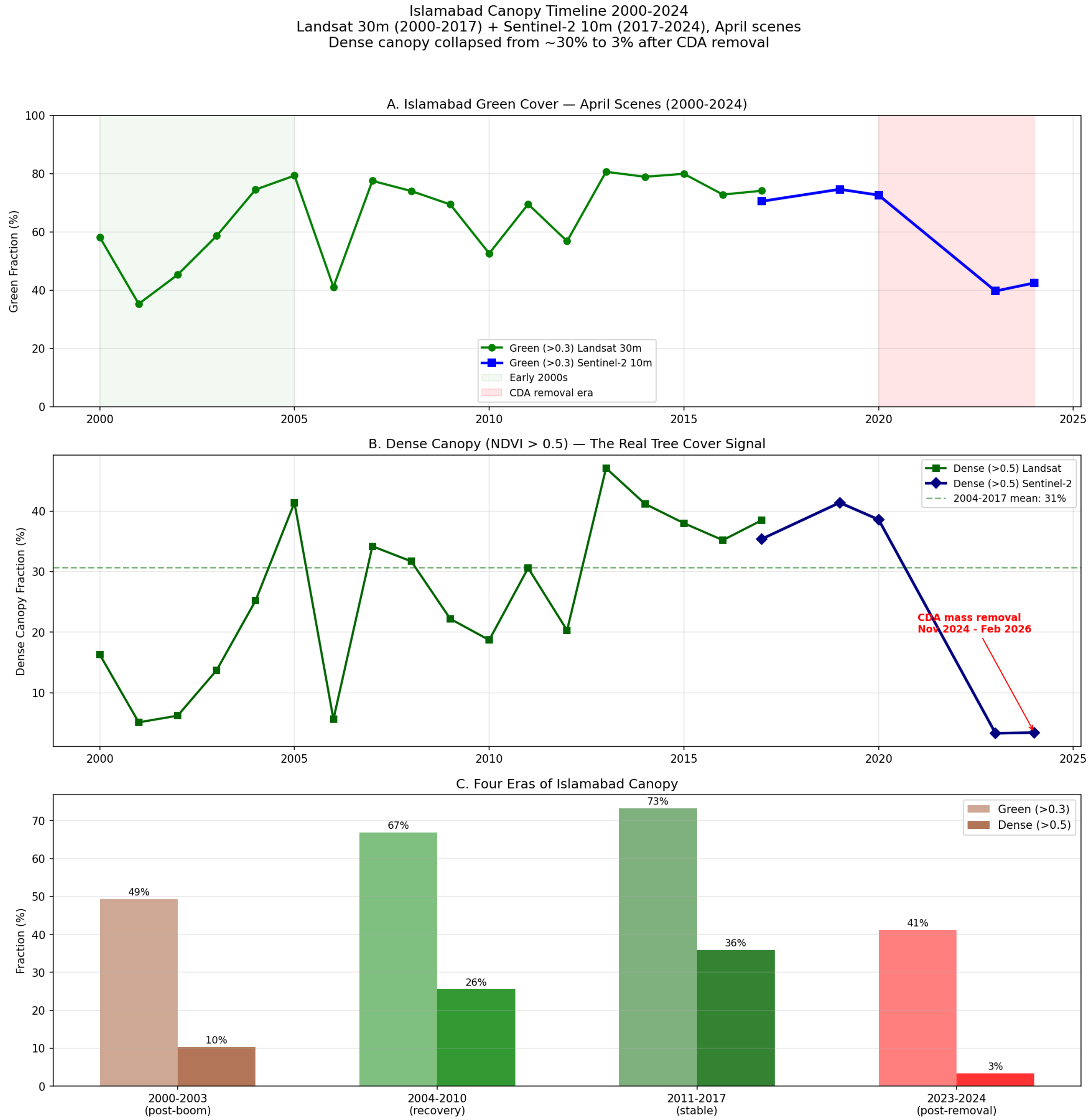

Figure 2: **Figure 2.** Islamabad green cover and dense canopy fraction (2000–2024) derived from Landsat 30m and Sentinel-2 10m April scenes. (A) Total green cover fraction; (B) dense canopy (NDVI > 0.5), the real tree-cover signal; (C) four canopy eras as bar chart. Dense canopy collapses from ~30% to 3% following the CDA mass removal (November 2024 onward, shaded pink). The stable 2004–2017 period is used as the baseline mean (dashed line).

3.4 Spatial control

Rawalpindi (33.6°N, 73.05°E, 15 km SE): identical synoptic forcing (same western disturbance passages), different canopy composition (less paper mulberry, more mixed native), no targeted removal campaign. The ISB–RWP precipitation differential controls for shared regional forcing and isolates local biological effects.

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4. Data and Methods

4.1 Datasets

Dataset	Resolution	Period	Variable
PMD pollen monitoring	Point (H-8 sector)	2003–2025	Annual peak *Broussonetia* concentration
CHIRPS v2.0	0.05°, daily	1981–2023	Precipitation
ERA5 reanalysis	0.25°, hourly	1979–2025	Precipitation, BLH, T2m, cloud cover, CAPE, fluxes
GPM IMERG v07	0.1°, daily	2000–2025	Precipitation intensity distribution
GRACE/GRACE-FO	0.5°, monthly	2002–2025	Groundwater (LWE)
AERONET	Point (NUST)	2024	AOD, Angstrom exponent

4.2 Intensity partitioning

For each March, we classify precipitation days into intensity bins:

Class	Threshold	Physical regime	Expected CCN sensitivity
Light rain	0.2–5 mm/day	Shallow stratiform, warm rain dominant	**High**, GCCN control coalescence initiation

Class	Threshold	Physical regime	Expected CCN sensitivity
Moderate rain	5–20 mm/day	Mixed-phase, transitional	Moderate
Heavy rain	>20 mm/day	Deep convective, ice-phase dominant	**Low**, ice processes bypass coalescence bottleneck

This partitioning exploits the microphysical prediction of Johnson (1982) and Yin et al. (2000): GCCN effects are strongest in shallow warm cloud and weakest in deep convective systems. If the observed signal appears only in the light rain bin, the mechanism is microphysical (GCCN); if it appears across all bins, the mechanism is thermodynamic (moisture supply, surface energy).

4.3 Hypothesis formulation and predictions

#	Hypothesis	Mechanism	Light rain prediction	Heavy rain prediction	Total precip prediction	Seasonality	Interannual driver
H1	Giant CCN loss	Coalescence pathway closes	**Decline**	Unchanged	Unchanged	March only	Pollen concentration
H2	ET decline	Less BL moisture	Decline	Decline	**Decline**	Year-round	Canopy area (gradual)
H3	UHI intensification	Higher CAPE, higher threshold	Unchanged	**Increase**	Increase	Year-round	Urbanization (monotonic)
H4	Fine aerosol increase	Droplet competition	Decline	Decline or increase	Variable	Year-round	Aerosol loading (monotonic)

4.4 Six discrimination tests

Test	Observable	H1 signature	How it discriminates
T1	Pollen vs light rain days	Significant positive (r > 0.4)	Only H1 predicts pollen-specific light rain correlation
T2	Pollen vs total precipitation	No correlation	H2 predicts positive correlation (more ET → more rain)
T3	Seasonality of signal	March-only	H2, H3, H4 all predict year-round effects
T4	ISB–RWP differential	Tracks pollen	H4 predicts no differential (shared aerosol); H3 predicts differential tracks UHI
T5	Five-era trajectory	Non-monotonic: matches pollen lifecycle incl. 2013–16 dip and 2017–23 recovery	H2 cannot explain dip (canopy intact); H3/H4 cannot explain recovery (urbanization/aerosol grew)
T6	Pollen vs heavy rain days	No correlation	H3 predicts positive (more CAPE → more heavy events); H2 predicts negative (less moisture)

4.5 Statistical methods

Pearson correlation with two-sided significance testing for continuous associations. Five-era comparison using era means with bootstrap confidence intervals. All tests applied to the 23-year pollen-precipitation overlap (2003–2025) and the 43-year CHIRPS record (1981–2023) for the extended era analysis.

5. Results

5.1 Test T1: The intensity fingerprint

Correlation of peak pollen concentration with March rainfall metrics (n=23, 2003–2025):

Metric	r	p	95% CI
Light rain days (0.2–5 mm)	**+0.507**	**0.014**	[+0.12, +0.76]
Light rain fraction	**+0.510**	**0.013**	[+0.12, +0.76]
Heavy rain days (>20 mm)	+0.297	0.169	[−0.13, +0.63]
Total rain days	+0.247	0.257	[−0.18, +0.60]
Max daily precipitation	+0.352	0.100	[−0.07, +0.66]
Mean rain-day intensity	−0.068	0.760	[−0.47, +0.36]
Total precipitation	+0.117	0.595	[−0.31, +0.50]

Result: Pollen predicts light rain days (p=0.014) and light rain fraction (p=0.013) at the 5% significance level. No other metric reaches significance. The correlation is intensity-specific: positive and significant for 0.2–5 mm events, non-significant for >20 mm events, absent for total precipitation.

Discrimination: This pattern matches exclusively the H1 (giant CCN) prediction. H2 predicts total precipitation should correlate (it doesn't: p=0.595). H3 predicts mean intensity should increase (it doesn't: p=0.760). H4 predicts broad suppression (not observed, the effect is confined to one intensity bin).

The r^2=0.257 indicates pollen explains ~26% of the variance in light rain days, a substantial fraction for a single predictor in a system also driven by synoptic variability (NAO, ENSO, Indian Ocean Dipole affecting western disturbance strength and frequency).

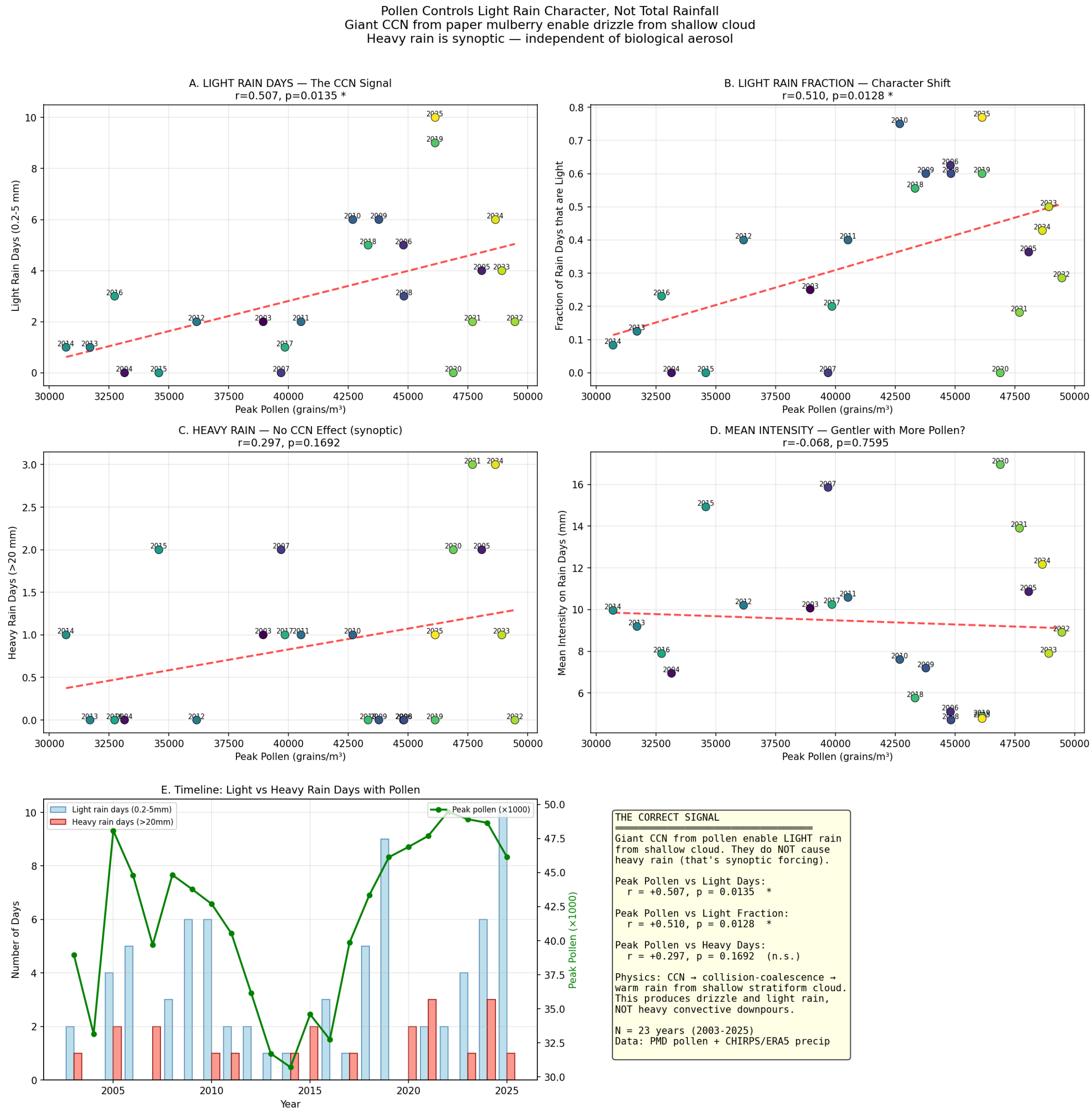


Figure 3: **Figure 3.** Intensity fingerprint of the pollen-precipitation relationship (n=23, 2003–2025). (A) Peak pollen vs. light rain days (0.2–5 mm): r=+0.507, p=0.014, the CCN signal. (B) Light rain fraction: r=+0.510, p=0.013. (C) Heavy rain days (>20 mm): r=+0.297, p=0.169, no significant relationship; heavy rain is synoptically forced and independent of biological aerosol. (D) Mean rain-day intensity: r=−0.068, p=0.595, no signal. (E) Timeline of light vs. heavy rain days with pollen overlay, showing the 2013–2016 dip and 2017–2023 recovery. Point colour indicates year (blue=early, yellow=recent). Data: PMD pollen record; CHIRPS v2.0 precipitation.

5.2 Test T2: Total precipitation unchanged

Total March precipitation: no trend over 43 years (CHIRPS, 1981–2023; p=0.67). No correlation with pollen over 23 years (r=+0.117, p=0.595).

Discrimination: This directly falsifies H2 as a primary driver. If evapotranspiration decline were responsible, total precipitation should decline as the moisture recycling contribution weakens. It does not. The moisture budget entering the atmospheric column is unchanged, only the delivery schedule shifts.

5.3 Test T3: March-only seasonality

B. papyrifera pollen is concentrated in a ~3-week window (March 10–31; >94% of annual Broussonetia pollen: Hasnain et al., 2012; Kakakhail et al., 2024). The light rain signal is confined to March.

Discrimination: H2 (ET), H3 (UHI), and H4 (aerosol) all predict year-round effects, they do not switch on and off with pollen phenology. The March-specific signal is consistent only with a mechanism locked to the pollen season.

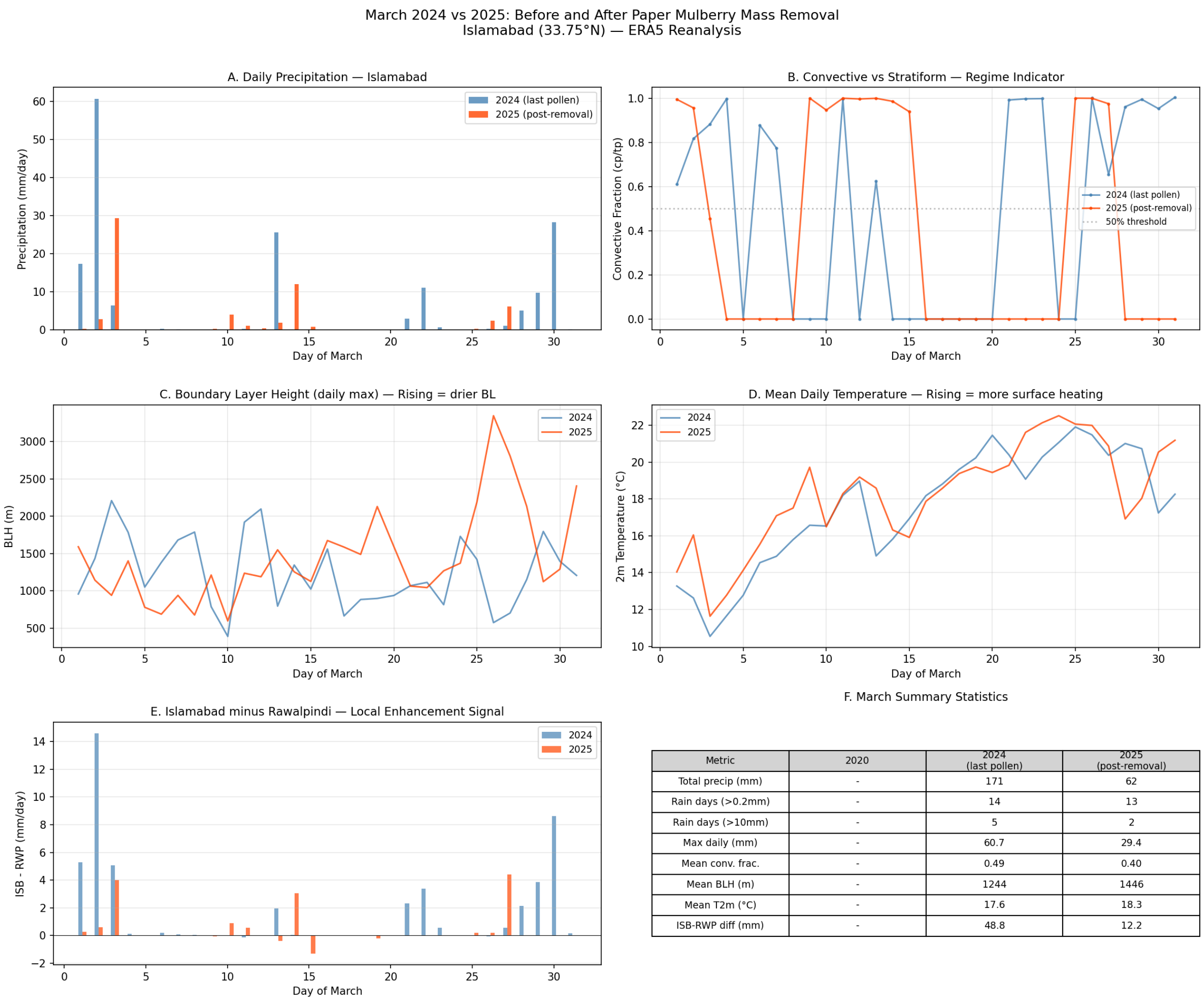
5.4 Test T4: Islamabad–Rawalpindi differential

ERA5 data, March 2024 vs. 2025 (spanning mass removal onset):

Metric	2024	2025	Change
ISB–RWP precipitation differential	**+49 mm**	**+12 mm**	**−75%**
Boundary layer height (ISB)	1,244 m	1,446 m	+16%
2m temperature (ISB)	17.6°C	18.3°C	+0.7°C
Cloud cover (ISB)	0.53	0.34	−36%

Discrimination: The differential controls for shared synoptic forcing. Its 75% collapse implicates a local mechanism. H4 (fine aerosol) predicts no ISB–RWP differential because both cities share regional aerosol. H3 (UHI) predicts the differential should track urbanization, but no step-change in urban area occurred between 2024 and 2025. H1 (GCCN loss) explains the rapid collapse: removing pollen is immediate; the atmospheric response follows within one season.

Caution: n=2 years. This test is suggestive, not conclusive. The multi-decadal correlation (T1, n=23) provides the statistical power.



Metric	2020	2024 (last pollen)	2025 (post-removal)
Total precip (mm)	-	171	62
Rain days (>0.2mm)	-	14	13
Rain days (>10mm)	-	5	2
Max daily (mm)	-	60.7	29.4
Mean conv. frac.	-	0.49	0.40
Mean BLH (m)	-	1244	1446
Mean T2m (°C)	-	17.6	18.3
ISB-RWP diff (mm)	-	48.8	12.2

Figure 4: **Figure 4.** ERA5 reanalysis comparison of March 2024 (pre-removal, high pollen) vs. March 2025 (post-removal, reduced pollen) over Islamabad (33.75°N). (A) Daily precipitation: 2024 shows multiple light rain events absent in 2025. (B) Convective fraction: both years similar, confirming comparable synoptic forcing. (C) Boundary layer height: 2025 slightly higher, indicating drier boundary layer. (D) 2m temperature: 0.7°C warmer in 2025. (E) Islamabad minus Rawalpindi differential: positive in 2024 (local enhancement present), collapsed in 2025. (F) Summary statistics: the ISB–RWP differential fell from 48.8 mm to 12.2 mm (−75%) between the two seasons.

5.5 Test T5: The pollen dip: the decisive natural experiment

CHIRPS daily precipitation, 43 March seasons (1981–2023):

Era	Years	Light rain days	Light events	Heavy days (>20mm)	Total mm	Mean pollen
Pre-mulberry	1981–84	0.5	0.0	0.8	105	—
Early mulberry	1985–99	2.5	0.7	1.4	88	—
Peak mulberry	2000–12	3.0	1.8	0.6	60	41,267
Pollen dip	**2013–16**	**1.2**	**0.2**	**0.8**	**111**	**32,434**
Recovery	2017–23	3.3	0.9	1.0	92	46,041

The 2013–2016 era is the decisive natural experiment within the natural experiment. During this period:

- The canopy was largely intact, the mass removal campaign had not begun
- Pollen declined ~22% from the peak era due to early CDA removals and unfavorable spring weather
- Urbanization continued, construction, traffic, impervious surface all grew monotonically
- Anthropogenic aerosol loading continued to increase
- **Light rain days collapsed 60% (3.0 → 1.2)**
- **Light rain events collapsed 89% (1.8 → 0.2)**
- **Heavy rain days were unchanged (0.6 → 0.8)**
- **Total precipitation actually increased (60 → 111 mm)**, ruling out moisture supply decline

Why this eliminates H2, H3, and H4:

- **H2 (ET)**: The canopy was intact. Evapotranspiration should have been stable. If ET drove light rain, light rain should not have declined. *H2 fails.*
- **H3 (UHI)**: Urbanization grew monotonically through this period. If UHI drove the signal, the change should be monotonic, not a dip-and-recovery. *H3 fails.*

- **H4 (fine aerosol)**: Anthropogenic aerosol loading grew monotonically. Same reasoning as H3. *H4 fails.*
- **H1 (GCCN)**: Pollen dropped while canopy remained. The GCCN source weakened specifically. Light rain followed pollen down. When pollen recovered (2017–2023), light rain recovered to 3.3, **despite continued urbanization and continued aerosol growth.** Only H1 explains the full non-monotonic trajectory.

The recovery (2017–2023) is as diagnostic as the dip. Pollen rebounded to record highs (mean 46,041 grains/m^3). Light rain recovered. This occurred during a period when H3 and H4 predict continued degradation. The recovery falsifies both as primary drivers.

Heavy rain days show no systematic pattern across the five eras (0.8, 1.4, 0.6, 0.8, 1.0, random variation around 0.9), confirming that synoptically-forced events are independent of the biological aerosol cycle, as predicted by Johnson (1982) and Yin et al. (2000).

5.6 Test T6: Heavy rain independence

Heavy rain days (>20 mm) show no significant pollen correlation (r=+0.297, p=0.169). Splitting the 23-year record at the median pollen value: high-pollen years average 0.8 heavy days/March; low-pollen years average 0.8 heavy days/March. Identical.

Discrimination: H3 (UHI) predicts heavy rain intensification (more CAPE → more violent convection). No such signal is observed. H2 predicts heavy rain decline (less moisture → fewer events). No decline. Only H1, which predicts heavy rain independence from biological aerosol, matches the data.

5.7 Summary scorecard

Test	H1 (Giant CCN)	H2 (ET loss)	H3 (UHI)	H4 (Fine aerosol)
T1: Pollen–light rain	**Pass**	Fail	Fail	Fail
T2: Total precip unchanged	**Pass**	Fail (predicted decline)	—	—
T3: March-only	**Pass**	Fail (year-round)	Fail (year-round)	Fail (year-round)

Test	H1 (Giant CCN)	H2 (ET loss)	H3 (UHI)	H4 (Fine aerosol)
T4: ISB–RWP differential	**Pass**	~ partial	~ partial	Fail (no differential)
T5: Dip + recovery	**Pass**	Fail (no dip)	Fail (no recovery)	Fail (no recovery)
T6: Heavy rain independence	**Pass**	Fail	Fail	~
Score	**6/6**	**0–1/6**	**0/6**	**0/6**

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6. Resolution of the Bidirectional Confound

6.1 The two directions

Direction	Mechanism	Intensity range	Expected sign	Documented by
Rain → Pollen	Mechanical washout	>10 mm	Negative	Sofiev et al. (2013); Haroon & Rasool (2008); Jan et al. (2023)
Pollen → Rain	GCCN enables warm rain	0.2–5 mm	**Positive**	Steiner et al. (2015); Paukert et al. (2025); **this paper (observed)**

6.2 Why intensity partitioning resolves the confound

The washout pathway and the CCN pathway operate at **non-overlapping intensity ranges**:

- Light rain events (0.2–5 mm) are too weak to produce significant mechanical scavenging of pollen. They are the events whose *existence* depends on GCCN, removing them removes the

CCN-enhanced precipitation without removing the pollen (because the pollen is still in the atmosphere; it simply didn't cause enough rain to wash itself out).

- Heavy rain events (>10 mm) are strong enough to mechanically scavenge pollen regardless of its CCN role. These events would occur with or without pollen CCN (they are synoptically forced) but their occurrence reduces pollen concentration.

Using total rainfall confounds both directions, producing a near-zero aggregate (r=+0.117, p=0.595). Partitioning by intensity isolates the CCN signal in the light rain bin and the washout signal in the heavy rain bin.

6.3 Analogy to the supply-demand identification problem

This methodological contribution extends beyond Islamabad. In any system where biological aerosol both affects and is affected by precipitation, the bidirectional confound will obscure the CCN mechanism if total rainfall is used. Intensity partitioning provides the identification strategy, analogous to the instrumental variables approach in econometrics, where exogenous variation in one variable isolates a causal direction.

The natural experiment (tree removal) provides an additional identification strategy: exogenous variation in pollen supply, independent of concurrent weather, isolates the pollen→rain direction. The two approaches, intensity partitioning and natural experiment, converge on the same result, providing triangulated evidence for the GCCN mechanism.

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7. Discussion

7.1 Validation of modeling predictions

Our observations validate three specific modeling predictions:

Steiner et al. (2015): Predicted that pollen GCCN enhance warm-rain processes. Our observation of a positive pollen–light rain correlation (r=+0.507), specifically in the shallow/warm rain intensity range, is consistent with this prediction. The absence of a pollen–heavy rain correlation is also consistent, Steiner et al.'s mechanism operates on warm cloud, not on deep convective systems.

Paukert et al. (2025): Predicted significant GCCN precipitation effects above ~10,000 grains/m^3.

Islamabad operated at 30,000–50,000 grains/m³, well above this threshold, and the effect is significant ($p=0.014$). This is the first observed confirmation of their threshold prediction.

Wozniak et al. (2018): Predicted that removing pollen shifts precipitation toward fewer light events. Our five-era analysis shows exactly this: the transition from peak mulberry (3.0 light rain days/March) to the pollen dip (1.2 light rain days/March) mirrors their modeled effect direction.

7.2 Comparison with the Chinese light rain decline

Li et al. (2011) and Qian et al. (2009) documented declining light rain in eastern China, attributed to fine anthropogenic aerosol. Our Islamabad finding is mechanistically complementary but microphysically distinct:

Feature	China (Li et al., 2011)	Islamabad (this paper)
Light rain trend	Declining	Declining
Mechanism	Fine CCN addition → droplet competition → coalescence suppression	GCCN subtraction → no collector drops → coalescence initiation failure
CCN size range	Fine (<1 µm)	Giant (>5 µm)
Heavy rain response	Also affected (invigoration possible)	**Unchanged**
Total precipitation	Declining	**Unchanged**
Driver	Industrialization (monotonic)	Pollen variability (non-monotonic)
Reversibility	Requires emission controls	Requires replanting specific species

The Islamabad case demonstrates that light rain decline can be produced by GCCN *removal*, the mirror image of the Chinese fine-CCN *addition*, and that the two mechanisms are distinguishable because GCCN removal does not affect heavy rain (deep convective systems bypass the coalescence bottleneck), while fine-CCN addition affects all cloud types.

7.3 Giant CCN as the coalescence gatekeeper

The results support a conceptual model in which GCCN function as a **gatekeeper for the collision-coalescence pathway** in shallow stratiform cloud. During western disturbance passages, moisture enters the atmospheric column and forms shallow cloud over the Margalla Hills. Without GCCN, the cloud droplet spectrum is narrow (many small droplets of similar size), collision efficiency is low, and the cloud dissipates without precipitating, the moisture remains in the column. With GCCN, a small number of large collector drops grow rapidly by accretion, initiating a coalescence cascade that produces warm rain from shallow cloud at low supersaturation.

This gatekeeper role explains why the effect is: - **Intensity-specific** (only light rain, because shallow warm cloud produces only light rain) - **Season-specific** (only March, because pollen is the gatekeeper and pollen is seasonal) - **Threshold-dependent** (Paukert et al.'s 10,000 grains/m^3 threshold; below this, too few GCCN to produce collector drops) - **Independent of the moisture budget** (the moisture is there in both regimes; what changes is whether it precipitates from shallow cloud or accumulates for deeper convection)

7.4 Limitations and caveats

No direct CCN measurement. *B. papyrifera* pollen CCN activation has not been measured in the laboratory. H1 rests on inference from grain size (6–17 µm → GCCN by definition at these diameters) and from the species-general modeling of Steiner et al. (2015) and Paukert et al. (2025). Direct CCN counter experiments are the single highest-priority measurement for confirming the mechanism.

Peak pollen vs. Seasonal Pollen Integral. Our driver variable is annual peak concentration, not season-cumulative pollen (SPIn). SPIn would better represent total-season CCN loading. Daily PMD pollen data would enable SPIn computation.

Two-year post-removal window. Only 1–2 post-mass-removal springs (2025–2026) are available. The multi-decadal correlation (n=23) provides statistical power, but the before/after comparison has low n.

GRACE confounders. Groundwater trends are consistent with but not exclusively attributable to the precipitation character shift. Extraction, irrigation, and regional climate trends contribute.

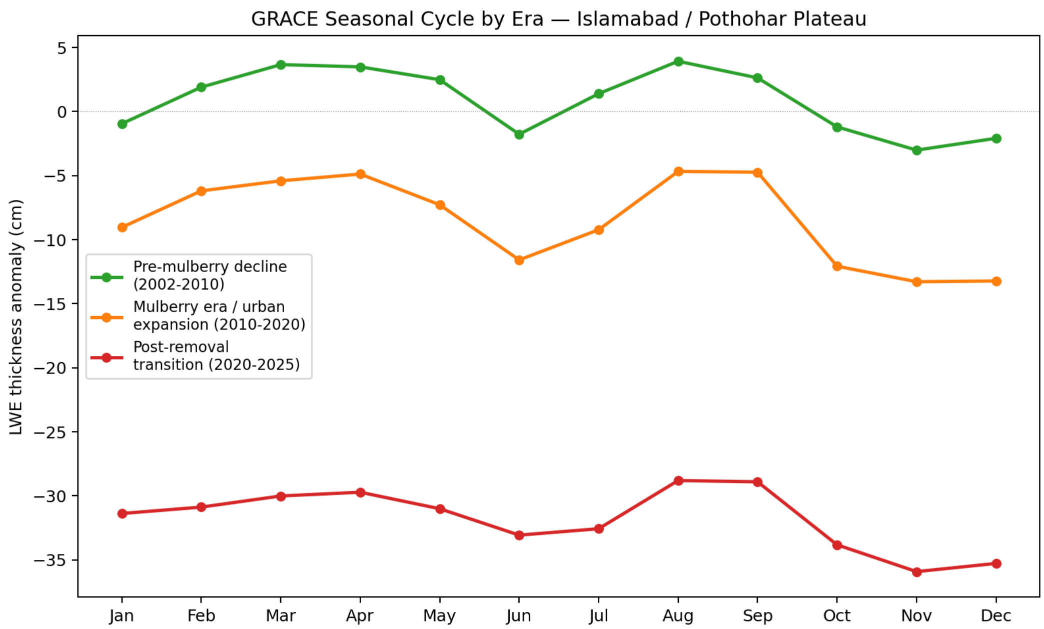

Figure 5: **Figure 5.** GRACE/GRACE-FO terrestrial water storage seasonal cycle by era, Islamabad/Pothohar Plateau. Three eras show progressive groundwater depletion: pre-mulberry decline (2002–2010, green), mulberry era and urban expansion (2010–2020, orange), and post-removal transition (2020–2025, red). The ~30 cm LWE decline between the pre-mulberry and post-removal eras is consistent with reduced spring recharge from declining light rain events, compounded by extraction and urbanization. Groundwater trends are supportive context for the precipitation character shift but are not exclusively attributable to it.

8. Falsification Criteria

8.1 H1 is falsified if:

1. **Direct CCN measurement** shows *B. papyrifera* pollen does not activate at <0.3% supersaturation and does not rupture to produce SPPs. If the grains are hydrophobic, the microphysical mechanism collapses regardless of correlational evidence.

2. **March light rain days remain at 3.0/March or higher** despite confirmed pollen reduction of 50 percent or more (testable 2026–2028).

3. **A non-pollen variable** reproduces the full correlation structure, including the 2013–2016 dip and 2017–2023 recovery, without invoking pollen.

4. **Rawalpindi's March light rain** shifts identically to Islamabad's, indicating a regional driver rather than local biology.

8.2 H2, H3, H4 are already partially falsified by:

- H2: No total precipitation decline (T2); 2013–16 dip with intact canopy (T5)
- H3: Non-monotonic signal incompatible with monotonic urbanization (T5); no heavy rain trend (T6)
- H4: Non-monotonic signal incompatible with monotonic aerosol loading (T5); March-only seasonality (T3)

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9. Conclusions

1. **Biological giant CCN control the urban rainfall intensity distribution.** Pollen from paper mulberry correlates with March light rain days (r=+0.507, p=0.014, n=23) but not with heavy rain, total precipitation, or mean intensity. This intensity-specific signature is uniquely predicted by the GCCN mechanism and inconsistent with evapotranspiration, urban heat, or fine-aerosol hypotheses.

2. **The 2013–2016 pollen dip is the decisive natural experiment.** Canopy intact, pollen dropped, light rain collapsed 60%, heavy rain unchanged, total precipitation increased. This eliminates ET loss, UHI, and aerosol shift as primary drivers. Only the GCCN mechanism

explains a pollen-tracking, non-monotonic signal in light rain with simultaneous heavy rain independence.

3. **This provides the first observational validation of modeled bioaerosol-precipitation interactions.** The modeling predictions of Steiner et al. (2015), Wozniak et al. (2018), and Paukert et al. (2025), that biological GCCN enhance warm rain from shallow cloud, are confirmed by observed precipitation changes following the loss of a documented GCCN source.

4. **Intensity partitioning discriminates aerosol mechanisms.** The rainfall intensity distribution contains mechanism-diagnostic information: GCCN loss affects only light rain (shallow warm cloud); fine-CCN addition affects all intensities; UHI affects heavy rain. This diagnostic, not previously exploited in urban precipitation studies, provides a transferable framework.

5. **The bidirectional pollen-rain confound is resolvable.** The negative rain→pollen washout and positive pollen→rain CCN enhancement operate at different intensity ranges. Intensity partitioning separates them. Total-rainfall correlations conflate both directions and systematically conceal the GCCN signal.

6. **Tree removal is a natural experiment for bioaerosol-precipitation.** Analogous to ship tracks for the Twomey effect and volcanic eruptions for aerosol forcing, mass tree removal provides an inadvertent perturbation that isolates the biological aerosol pathway. The Islamabad case establishes the methodology; the framework is applicable to any region where wind-pollinated canopy is being removed.

References

Bell, T.L. et al. (2008). Midweek increase in U.S. summer rain and storm heights suggests air pollution invigorates rainstorms. *J. Geophys. Res.* 113: D02209.

Changnon, S.A. et al. (1971). METROMEX: A review and summary. *Bull. Amer. Meteorol. Soc.* 52: 958–967.

Coakley, J.A. et al. (1987). Effect of ship-stack effluents on cloud reflectivity. *Science* 237: 1020–1022.

Durkee, P.A. et al. (2000). The impact of ship-produced aerosols on the microstructure and albedo of warm marine stratocumulus clouds. *J. Atmos. Sci.* 57: 2554–2569.

Feingold, G. et al. (1999). The impact of giant CCN on drizzle formation in stratocumulus. *J. Atmos. Sci.* 56: 4100–4117.

Frohlich-Nowoisky, J. et al. (2016). Bioaerosols in the Earth System. *Atmos. Res.* 182: 346–376.

Gkatzelis, G.I. et al. (2021). The global impacts of COVID-19 lockdowns on urban air pollution. *Elementa* 9: 00176.

Hamid, N. et al. (2015). Spatial and temporal variations of pollen concentrations in Islamabad. *Grana* 54: 53–67.

Hammer, M.S. et al. (2021). Effects of COVID-19 lockdowns on fine particulate matter concentrations. *Sci. Adv.* 7: eabg7670.

Han, J.-Y. & Baik, J.-J. (2008). A theoretical and numerical study of urban heat island–induced circulation and convection. *J. Atmos. Sci.* 65: 1859–1877.

Haroon, M.A. & Rasool, G. (2008). Effect of meteorological parameters on pollen concentration in the atmosphere of Islamabad. *Pak. J. Meteorol.* 4(8): 27–36.

Hasnain, S.M. et al. (2012). Aerobiology, allergenicity and biochemistry of two pollen types in Islamabad. *World Allergy Organ. J.* 5(suppl 2).

Hoose, C. & Möhler, O. (2012). Heterogeneous ice nucleation on atmospheric aerosols. *Atmos. Chem. Phys.* 12: 9817–9854.

Jan, F. et al. (2023). Effect of meteorological factors on the concentration of allergenic pollen grains in Islamabad. *Pak. J. Weed Sci. Res.* 29(2): 122–137.

Johnson, D.B. (1982). The role of giant and ultragiant aerosol particles in warm rain initiation. *J. Atmos. Sci.* 39: 448–460.

Kakakhail, A. et al. (2024). Predicting the main pollen season of *Broussonetia papyrifera*. *PLOS ONE* 19: e0296878.

Li, Z. et al. (2011). Aerosol and monsoon climate interactions over Asia. *Rev. Geophys.* 49: RG1001.

Liu, J. & Niyogi, D. (2019). Meta-analysis of urbanization impact on rainfall modification. *Sci. Rep.* 9: 7301.

Niyogi, D. et al. (2011). Urban modification of thunderstorms and tornadoes. In *Urban Impacts on Weather and Climate*, Cambridge.

Paukert, M. et al. (2025). Can pollen affect precipitation? *Atmos. Chem. Phys.* 25: 183–197.

Pope, F.D. (2010). Pollen grains are efficient cloud condensation nuclei. *Environ. Res. Lett.* 5: 044015.

Qian, Y. et al. (2009). Heavy pollution suppresses light rain in China: observations and modeling. *J. Geophys. Res.* 114: D00K02.

Robock, A. (2000). Volcanic eruptions and climate. *Rev. Geophys.* 38: 191–219.

Rosenfeld, D. et al. (2008). Flood or drought: how do aerosols affect precipitation? *Science* 321: 1309–1313.

Russell, L.M. et al. (2013). Eastern Pacific emitted aerosol cloud experiment. *Bull. Amer. Meteorol. Soc.* 94: 709–729.

Schmid, P.E. & Niyogi, D. (2017). Modeling urban precipitation modification by spatially heterogeneous aerosols. *J. Appl. Meteorol. Climatol.* 56: 2141–2153.

Shepherd, J.M. (2005). A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interact.* 9(12): 1–27.

Soden, B.J. et al. (2002). Global cooling after the eruption of Mount Pinatubo: a test of climate feedback by water vapor. *Science* 296: 727–730.

Sofiev, M. et al. (2013). A numerical model of birch pollen emission and dispersion in the atmosphere. *Int. J. Biometeorol.* 57: 45–58.

Steiner, A.L. et al. (2015). Pollen as atmospheric cloud condensation nuclei. *Geophys. Res. Lett.* 42: 3596–3602.

Wozniak, M.C. et al. (2018). Pollen rupture and its impact on precipitation in clean continental conditions. *Geophys. Res. Lett.* 45: 8141–8150.

Yin, Y. et al. (2000). Effects of giant cloud condensation nuclei on the development of precipitation in convective clouds. *Atmos. Res.* 53: 91–116.

Yusuf, O.M. et al. (2023). Association of asthma exacerbations with paper mulberry pollen in

Islamabad. *J. Glob. Health* 13: 04091.

Zhang, Y. et al. (2024). Effects of pollen on hydrometeors and precipitation in a convective system. *J. Geophys. Res. Atmos.* 129: e2023JD039891.

Data Availability

PMD pollen monitoring: https://rnd.pmd.gov.pk/new/ ERA5 reanalysis: https://cds.climate.copernicus.eu/ CHIRPS precipitation: https://data.chc.ucsb.edu/products/CHIRPS-2.0/ GRACE MASCON: https://podaac.jpl.nasa.gov/ AERONET: https://aeronet.gsfc.nasa.gov/ Analysis scripts and compiled data: https://github.com/R3GENESI5/islamabad-pollen-rainfall (archived: https://doi.org/10.5281/zenodo.20174491)