Evapotranspiration Trapping at Low Atmospheric Levels

A Thermodynamic Analysis of Residential Microclimate Cooling in Arid Environments

Robert C. Brandys, PhD, MPH, PE
OEHCS, Las Vegas, Nevada

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Abstract

This paper introduces the concept of *evapotranspiration trapping at low atmospheric levels* — a phenomenon in which plant-transpired moisture accumulates within geometrically enclosed air bodies near ground level, producing sustained air temperature depressions of 15–20°F (8–11°C) in arid climates. Through field observations at four residential microclimates in Las Vegas, Nevada (ambient summer conditions: 110°F / 43°C, ~10% RH), and energy balance modeling, we demonstrate that the combination of high evapotranspiration rates, wind-blocking enclosure geometry, and dense canopy coverage creates a synergistic cooling effect that is multiplicative rather than additive. We propose a quantitative classification system based on the ET/Solar ratio to distinguish four microclimate types: Canopy Shade, Canyon Shade, Corridor, and ET Trapping. The energy balance model shows that enclosed residential yards with sufficient irrigation, canopy coverage, and wall closure on a minimum of three sides can achieve cooling capacities exceeding 100× the thermodynamic requirement, with the practical limit being the psychrometric wet bulb temperature.

1. Introduction

Las Vegas, Nevada represents one of the most extreme urban heat environments in North America, with summer ambient temperatures routinely exceeding 110°F (43°C) and relative humidity below 10%. The urban heat island effect, extensively documented by researchers at UNLV, compounds these conditions. Saher et al. (2021) found that vegetation produces a cooling effect of 5.6°C in Las Vegas — the highest of all cities studied — owing to the extreme aridity that amplifies the thermodynamic benefit of each unit of evapotranspired moisture.

While the physics of evapotranspiration cooling are well established, and the architecture of courtyard microclimates has been studied in Mediterranean and Middle Eastern contexts, a specific mechanism has remained unnamed: the geometric trapping of plant-transpired moisture at low atmospheric levels within residential-scale enclosures. This paper documents that phenomenon through comparative analysis of four microclimates spanning a spectrum from pure shade effects to full ET trapping.

2. Theoretical Framework

2.1 Energy Balance Model

The temperature depression ΔT within an enclosed microclimate is determined by the balance between evapotranspiration cooling and the sum of all heat gains. The steady-state energy balance for the enclosed air body is:

$$\mathbf{Q_{ET}} = \mathbf{Q_{solar}} + \mathbf{Q_{conv}}(\Delta T) + \mathbf{Q_{wall}}(\Delta T) + \mathbf{Q_{IR}}$$

Solving for ΔT:

$$\mathbf{\Delta T = (Q_{ET} - Q_{solar,ground} - Q_{wall,solar} - Q_{IR}) / (Q_{conv/°F} + Q_{wall/°F})}$$

Subject to the psychrometric ceiling: $\Delta T \leq T_{ambient} - T_{wet\ bulb}$

2.2 Component Equations

Evapotranspiration Cooling (Q_{ET})

The cooling power of evapotranspiration is derived from the latent heat of vaporization of water (1,037 BTU/lb; 8,649 BTU/gallon):

$$Q_{ET} = (V_{irr} \times f_{ET} \times K_{canopy} \times K_{fert} / t_{peak}) \times 8.34 \times 1{,}037$$

Where:

- V_{irr} = daily irrigation volume (gallons/day)
- f_{ET} = fraction of irrigation converted to ET (~0.85 for amended soils)
- K_{canopy} = canopy coverage factor (0–1.0)

- K_{fert} = fertilization multiplier (1.0–1.3 depending on nutrient regime)
- t_{peak} = peak cooling hours per day (~10 hours)

Solar Heat Gain to Ground ($Q_{solar,ground}$)
A critical insight of this model is that canopy does not add heat to the air body — it acts as an energy converter, intercepting solar radiation and using it to drive transpiration. Only solar energy reaching the ground surface becomes a sensible heat gain:

$$Q_{solar} = I_{solar} \times A_{ground} \times [(1 - f_{shade})(1 - \alpha) + f_{shade} \times 0.15 \times (1 - \alpha)] \times 0.60$$

Where I_{solar} is the solar irradiance (BTU/hr·ft²), A_{ground} is total ground area, f_{shade} is the shade fraction, α is the ground albedo, and the 0.60 factor accounts for ground-to-air heat transfer efficiency.

Convective Heat Gain (Q_{conv})
Convective exchange with ambient air is the primary pathway by which the cooled air body equilibrates with its surroundings:

$$Q_{conv} = ACH \times V \times \rho_{air} \times c_p \times \Delta T$$

Where ACH is the air changes per hour, V is the enclosure volume (ft³), ρ_{air} = 0.065 lb/ft³, and c_p = 0.24 BTU/lb·°F. The ACH for an open-top walled enclosure is modeled as:

$$ACH = ACH_{base} + k_{wind} \times v_{ambient} \times (1 - f_{wind\ reduction})$$

Where ACH_{base} accounts for thermal-driven ventilation (~2 hr^{-1}) and k_{wind} is the wind coupling coefficient (~3 hr^{-1}/mph).

Wall Conduction (Q_{wall})
Heat conducted through walls has two components: a fixed solar absorption term and a ΔT-dependent conduction term:

$$Q_{wall} = U_{wall} \times A_{wall} \times \Delta T + I_{solar} \times A_{wall,exposed} \times \alpha_{wall} \times 0.40$$

Where U_{wall} is the wall thermal conductance (BTU/hr·ft²·°F), and the 0.40 factor represents the fraction of absorbed solar energy conducted inward versus re-radiated outward.

2.3 Psychrometric Ceiling

The maximum possible evaporative cooling is bounded by the wet bulb temperature. At Las Vegas summer conditions (110°F, 10% RH), the wet bulb temperature is approximately 71°F, yielding a theoretical maximum cooling of 39°F. The observed 20°F

depression represents 51% of this theoretical maximum — well within achievable limits for a partially enclosed system.

Parameter	Value	Parameter	Value
Ambient temperature	110°F (43°C)	Wet bulb temperature	71°F (22°C)
Relative humidity	~10%	Max theoretical cooling	39°F (22°C)
Observed cooling	~20°F (11°C)	% of theoretical max	51%

Table 1. Psychrometric validation of observed cooling at JMW site.

3. The Trapping Mechanism

Existing literature extensively documents evapotranspiration as a thermodynamic cooling process, courtyard microclimates as an architectural form, and urban heat island mitigation through vegetation. What has not been explicitly named or quantified is the specific mechanism by which plant-transpired moisture accumulates within geometrically enclosed air bodies at human activity level.

We define **evapotranspiration trapping at low atmospheric levels** as the phenomenon in which:

1. Plant transpiration releases water vapor into a geometrically enclosed air body near ground level (below 10 ft / 3 m)
2. Physical barriers (walls, roofs, dense canopy) prevent advective and convective removal of the humid air
3. The trapped moisture accumulates, progressively raising local humidity and lowering temperature through the latent heat mechanism
4. The system reaches dynamic equilibrium where ET input balances leakage, maintaining a sustained temperature depression
5. The effect is amplified in arid climates because the extreme vapor pressure deficit means each unit of transpired moisture produces outsized cooling

3.1 The Three-Factor Synergy

Sensitivity analysis using the energy balance model reveals that the three dominant factors — evapotranspiration rate, wind blocking, and canopy shading — interact multiplicatively rather than additively. Removing any single factor collapses the cooling effect disproportionately:

Configuration	ET (BTU/hr)	ACH	Predicted ΔT
Full system (JMW)	147,026	~13	39°F (at ceiling)
Remove walls (open yard)	147,026	~78	~2°F
Remove ET (no irrigation)	~800	~13	~0°F
Remove canopy (bare soil)	~5,000	~20	Net heating

Table 2. Sensitivity analysis demonstrating multiplicative interaction of the three factors.

3.2 Wall Closure Geometry

Analysis of the case study sites establishes a minimum geometric requirement for ET trapping: enclosure on at least three of four sides with walls of sufficient height (≥6 ft / 1.8 m), with the opening not oriented toward the prevailing wind direction. In Las Vegas, where prevailing summer winds are from the southwest, an opening on the north or east side preserves the trapping effect while allowing some natural ventilation.

The critical parameter is the air change rate (ACH). Walled enclosures reduce ACH from 60–80 hr^{-1} (open yard) to 5–15 hr^{-1} (enclosed yard), increasing moisture residence time from seconds to 30–60 minutes. This extended residence time is what allows transpired moisture to accumulate to thermodynamically significant concentrations.

4. Comparative Case Studies

Four microclimates were analyzed in residential Las Vegas to isolate the contribution of each factor along the spectrum from pure shade effects to full ET trapping.

4.1 MC1 — Front Courtyard (Canyon Shade)

A 10′ × 12′ courtyard enclosed on three sides by 12-foot walls (garage, living room, foyer), open on the east side to a 3-foot sidewalk. Height-to-width ratio of 1.2:1 creates a deep urban canyon receiving zero direct sunlight. Vegetation consists of 50-year-old roses and Ajuga ground cover, irrigated by 2–4 GPD of passive condensation from an instant water heater. Soil is 100% amended potting soil.
The energy balance model predicts ΔT ≈ 0–3°F. ET cooling capacity (1,616 BTU/hr) barely exceeds the fixed heat gains from wall conduction and reflected solar radiation. The dominant cooling mechanism is thermal mass of the 12-foot concrete walls retaining nighttime cool air, not evapotranspiration. ET/Solar ratio: 1.13.

4.2 MC2 — Olive Tree Canopy (Canopy Shade)

A 30′ × 30′ open front yard with a 50-year-old olive tree providing 90% measured shade (daily weighted average ~72%). No walls. Vegetation at 35% ground coverage consisting of cacti and native species on unamended desert soil (albedo 0.30). Drip irrigation delivers ~15 GPD via 30 feet of perforated 1/4-inch line at 30 gal/hr for 30 minutes.
The model predicts ΔT ≈ 0°F air temperature depression. ET cooling capacity (757 BTU/hr) is negligible against the solar heat load reaching 900 ft² of ground (41,000 BTU/hr). With no walls, ACH reaches 78 hr^{-1}, dissipating any transpired moisture within seconds. Observers perceive shade comfort (reduced radiant heating of skin) but the air thermometer shows no measurable change. ET/Solar ratio: 0.02.

4.3 MC3 — Vegetable Corridor (Corridor Type)

An 8′ × 70′ raised-bed vegetable garden running east–west between the south wall of a garage (north side) and an 8-foot concrete block wall (south side). Both walls painted white, increasing measured winter light levels by 300% through reflection. Raised beds are 18” tall with amended soil/compost and wood mulch. Crops include a 15-year-old mandarin orange, 3-year-old pepper plants, asparagus, tomatoes, beans, snow peas, sweet potatoes, and Malabar spinach.
This corridor exhibits no significant summer cooling because its east–west orientation aligns with the prevailing southwest wind, creating a wind tunnel effect (ACH > 100 hr^{-1}). However, it functions as a winter thermal shelter: the white walls reflect low-angle winter sunlight, and the corridor geometry blocks cold north winds, enabling freeze-sensitive species to survive. The 15-year-old mandarin and 3-year-old pepper plants serve as indicator species proving sustained winter microclimate benefit.

4.4 JMW — Tropical Yard (ET Trapping)

The primary case study: a 15′ × 50′ rear yard (plus side yards totaling ~1,250 ft²) enclosed by 6-foot concrete block walls on three sides, with a house on the north side and a patio roof covering 10 feet of depth. The property owner, originally from Hawaii, established tropical fruit trees including papaya (K_c 1.0–1.5), guava (K_c 0.8–1.0), banana (K_c 1.1–1.2), jacaranda, and various tropical species. Total estimated irrigation: 200 GPD. Soil amended with >50% compost in a chicken manure fertilization cycle. Overall shade: 81%, canopy coverage: 80%, wind reduction: 90%.

The model predicts ΔT = 39°F (hitting the psychrometric wet bulb ceiling), indicating massive overcapacity. Observed cooling of ~20°F represents 51% of the theoretical maximum, consistent with the higher-than-modeled ACH expected for an open-top enclosure. ET cooling capacity is 147,026 BTU/hr against a solar load of 57,565 BTU/hr, yielding an ET/Solar ratio of 2.55 — firmly in the ET Trapping classification. Daily transpiration produces approximately 170 gallons of water vapor entering the enclosed atmosphere.

4.5 Comparative Summary

Parameter	MC1 Courtyard	MC2 Olive Trees	MC3 Corridor	JMW Tropical
Area	120 ft²	900 ft²	560 ft²	1,250 ft²
Wall height	12 ft (3 sides)	None	8 ft (2 sides)	6 ft (3 sides)
Shade	98%	72%	Variable	81%
Wind reduction	93%	30%	~0% (aligned)	90%
Irrigation (GPD)	3	15	Moderate	200
Canopy coverage	65%	35%	~40%	80%
Soil type	Potting soil	Native caliche	Amended/compost	>50% compost
ET (BTU/hr)	1,616	757	Low	147,026
Solar load (BTU/hr)	1,426	41,066	High	57,565
ACH (hr^{-1})	~7	~78	>100	~13
ET/Solar ratio	1.13	0.02	<0.10	2.55
Observed ΔT	<5°F	~2°F (shade)	None (summer)	~20°F
Classification	Canyon Shade	Canopy Shade	Corridor	ET Trapping

Table 3. Comparative analysis of four residential microclimates in Las Vegas, NV.

5. Microclimate Classification System

Based on the comparative analysis, we propose a four-type classification system using the ET/Solar ratio as the primary diagnostic metric. This ratio captures the balance between evaporative cooling capacity and solar heat input, providing a single dimensionless number that discriminates between fundamentally different cooling mechanisms.

Type	ET/Solar Ratio	Dominant Mechanism	Geometry Req.	Expected ΔT
Canopy Shade	<0.10	Radiant heat blocking	Tree canopy, no walls	1–3°F (perceived)
Canyon Shade	0.10–0.50	Thermal mass + shade	High walls (≥3 sides)	3–5°F
Corridor	<0.10*	Seasonal wind/light mod.	2 parallel walls	Variable†
ET Trapping	>1.50	Evapotranspiration + containment	≥3 walls + canopy + irrigation	15–20°F+

*Table 4. Proposed microclimate classification system. *Corridor ET/Solar ratio is low due to high air exchange. †Corridor provides winter warming, not summer cooling.*

The ET/Solar ratio is computed as $Q_{ET} / Q_{solar,ground}$, where both terms are evaluated at peak summer conditions. A ratio above 1.50 indicates that the evapotranspiration

system generates more than 50% excess cooling capacity beyond what is needed to offset the solar heat load — the signature of ET trapping.

6. Discussion

6.1 The Canopy as Energy Converter

A key insight from the energy balance modeling is that plant canopy should not be treated as a heat source or heat sink, but as an energy converter. When solar radiation strikes a leaf surface, the absorbed energy is partitioned into sensible heat (warming the leaf and surrounding air) and latent heat (driving transpiration). In well-watered tropical species, the latent heat fraction dominates: the Bowen ratio (β = sensible/latent) approaches 0.2–0.4, meaning 70–80% of absorbed solar energy is channeled into evapotranspiration.

This means that dense canopy in a walled enclosure is not simply blocking solar radiation (as in the Canopy Shade type) but actively converting it into cooling power. The more solar energy the canopy intercepts, the more water it transpires, and the cooler the enclosed air becomes — provided the moisture is trapped by the enclosure geometry.

6.2 Model Overcapacity and the ACH Question

The energy balance model predicts cooling to the psychrometric ceiling (39°F) at the JMW site, while the observed cooling is approximately 20°F. This discrepancy points to the model underestimating the actual air change rate. An open-top enclosure with 6-foot walls in a desert environment experiences significant thermal-driven ventilation as the cooled, dense air body is displaced by lighter warm air drawn over the wall tops. Calibrating the model to match the observed 20°F depression requires ACH ≈ 25–30 hr^{-1}, compared to the modeled 13 hr^{-1}. This represents an important area for future instrumented measurement.

6.3 Arid Climate Amplification

The ET trapping effect is strongly amplified in arid climates for two reasons. First, the large vapor pressure deficit means each unit of transpired water produces a larger temperature drop per unit of air. Second, the background humidity is so low that even modest moisture accumulation produces a measurable psychrometric shift. Saher et al. (2021) quantified this at the urban scale, finding vegetation cooling of 5.6°C in Las Vegas versus 1.4°C in Miami. The ET trapping mechanism operates at the residential scale as a concentrated version of this same physics.

6.4 Design Implications

The findings suggest specific design guidelines for creating ET trapping microclimates in arid residential settings. Enclosure on at least three sides with walls of 6 feet or greater, with the opening oriented away from prevailing winds; dense, high-K_c vegetation with canopy coverage exceeding 70%; irrigation sufficient to support full crop evapotranspiration (guided by FAO 56 crop coefficients); and amended soils with high organic content to maximize water retention in the root zone. The fertilization feedback

loop — where nutrient-rich soil grows larger canopies that transpire more water — represents a self-amplifying system that should be intentionally cultivated.

7. References

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Appendix A: Plant Water Use Summary

Species	Kc (mid)	Daily Water Use	ET Contribution	Notes
Papaya	1.0–1.5	5–10 gal/tree	High	Very high transpiration; large LAI
Guava	0.8–1.0	3–8 gal/tree	Moderate-High	Robust in heat
Banana	1.1–1.2	5–10 gal/plant	High	High ET, broad leaves
Jacaranda	0.5–0.7	15–30 gal/tree	High (canopy)	Major shade provider
Mango*	0.75–1.05	5–15 gal/tree	Moderate-High	Probable; needs confirm
Plumeria*	0.3–0.5	1–3 gal/tree	Low-Moderate	Ornamental

*Table A1. Crop coefficients and estimated water use for species at JMW site. *Probable species pending confirmation.*

Appendix B: Key Constants and Conversions

Parameter	Value	Unit
Latent heat of vaporization	1,037	BTU/lb
Water density	8.34	lb/gallon
Latent heat per gallon	8,649	BTU/gallon
Air density	0.065	lb/ft³
Air specific heat (cp)	0.24	BTU/lb·°F
DXA per inch	1,440	DXA/inch
Las Vegas summer ETo	0.35	in/day (8.9 mm/day)
Las Vegas summer solar	~300	BTU/hr·ft² peak
Solar noon altitude (summer)	77.5°	at 36°N latitude

Table B1. Key physical constants and Las Vegas environmental parameters used in the energy balance model.