Quantifying Cumulative Ultraviolet Radiation Dose in Desert Microclimates:

A Gaussian Model and Peak-Weighted Shade Factor Classification System for the Las Vegas Valley

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Abstract

Current horticultural guidance for the Las Vegas Valley relies on single-point, peak-intensity ultraviolet (UV) radiation measurements to characterize plant exposure environments. This approach fails to account for the cumulative nature of UV-induced tissue damage, which is a function of both radiation intensity and duration of exposure—the total dose. This paper presents three contributions to desert microclimate science: (1) a mathematical model demonstrating that clear-sky diurnal UV irradiance at Las Vegas latitude (36.17°N) follows a Gaussian distribution characterized by amplitude A, center μ (solar noon), and width σ (seasonally variable from 1.81 to 2.75 hours); (2) a three-point field measurement protocol that characterizes the complete daily UV dose curve from just three strategically timed readings; and (3) the Peak-Weighted Shade Factor (PWSF), a novel quantitative metric that classifies desert microclimates (MC-0 through MC-5) based on the fraction of cumulative daily UV dose blocked by shading features, weighted by the timing of shade relative to peak irradiance. The PWSF enables, for the first time, a rigorous mapping between microclimate shading characteristics and plant species viability that accounts for the dose-response relationship between UV exposure and plant tissue damage. Results demonstrate that a two-hour midday shade window centered on solar noon reduces cumulative UV dose by 24%, while the same two hours of shade in early morning provides only a 10–12% reduction—a difference invisible to single-point measurement approaches.

Keywords: ultraviolet radiation dose, microclimate classification, Gaussian distribution, solar irradiance, desert horticulture, Las Vegas, Peak-Weighted Shade Factor, cumulative UV exposure, plant viability

1. Introduction

The Las Vegas Valley presents one of the most extreme horticultural environments in the United States. Located at 36.17°N latitude and 610 meters elevation in the Mojave Desert, the valley receives among the highest annual solar radiation doses of any populated area in North America. Peak UV Index values routinely exceed 11 during summer months, and the region's

characteristically low humidity (often below 20%), minimal cloud cover (over 290 clear days per year), and high surface reflectivity from light-colored desert soils create conditions where UV radiation poses a significant and often underrecognized threat to plant survival.

A central deficiency in current guidance is the treatment of UV radiation as a single-point intensity measurement—typically the peak UV Index at solar noon. While peak UVI is useful for public health messaging, it is an inadequate metric for characterizing the radiation environment experienced by a plant, which is rooted in one location for months or years. Plant tissue damage from UV radiation, like human sunburn, is a dose-response phenomenon: it depends not only on intensity but on the cumulative energy absorbed over time. A plant in a microclimate that receives moderate UV for 14 hours may accumulate more tissue damage than one receiving extreme UV for 6 hours. This distinction is invisible to single-point measurements.

This paper addresses this gap by developing a quantitative framework for characterizing desert microclimates based on cumulative UV dose. We present three integrated contributions: a mathematical model of diurnal UV irradiance, a practical field measurement protocol, and a classification system that maps microclimate shading characteristics to plant species viability.

2. Theoretical Framework

2.1 Diurnal UV Irradiance as a Gaussian Distribution

The instantaneous UV irradiance at Earth's surface is governed by the solar zenith angle and atmospheric attenuation. The solar zenith angle θz at any time is given by the spherical law of cosines:

$$cos(\theta_z) = sin(\varphi)sin(\delta) + cos(\varphi)cos(\delta)cos(h)$$

where φ is latitude, δ is solar declination, and h is the hour angle (15° per hour from solar noon). Atmospheric attenuation follows the Beer-Lambert Law, with transmittance decreasing exponentially with the optical path length, which is inversely proportional to cos(θz). The resulting surface irradiance is the product of a cosine projection effect and an exponential atmospheric absorption term:

$$I(t) = I_0 \cdot cos(\theta_z) \cdot \tau^{AM \cdot P/P0}$$

where I_0 is the extraterrestrial UV irradiance, τ is the atmospheric transmittance coefficient, AM is the air mass (Kasten-Young, 1989), and P/P_0 is the pressure ratio for elevation correction. The combined effect of the cosine projection and exponential attenuation produces a diurnal curve that is narrower and more peaked than a pure cosine function. Empirical analysis confirms that this curve is well-approximated by a Gaussian distribution:

$$I(t) = A \cdot exp(-(t - \mu)^2 / (2\sigma^2)) \quad \text{(Eq. 1)}$$

where A is the peak irradiance at solar noon (W/m²), μ is the time of solar noon (hours), and σ is the width parameter (hours). This Gaussian approximation has been independently confirmed in the literature (Guo and Zhang, 2015) for clear-sky conditions, and our analysis of NOAA solar radiation data for Las Vegas validates its applicability at this latitude.

2.2 Seasonal Variation of the Gaussian Width Parameter

The width parameter σ varies systematically with day length, which is itself a function of latitude and solar declination. For the UV spectrum specifically, σ is narrower than for total solar radiation (Global Horizontal Irradiance, GHI) because shorter wavelengths suffer greater Rayleigh scattering and ozone absorption at low sun angles, effectively suppressing the tails of the UV curve more than the visible/infrared tails. Our model yields the empirical relationship:

$$\sigma_{UV} \approx 0.19 \times D_L \quad \text{(Eq. 2)}$$

where D_l is the day length in hours. Table 1 presents the seasonal Gaussian parameters for Las Vegas.

Table 1. Seasonal UV Gaussian parameters for Las Vegas, NV (36.17°N, 610 m elevation).

Date	Day Len (h)	σ UV (h)	FWHM (h)	Peak UV (W/m²)	Peak UVI	Daily Dose (SED)
Jan 15	9.8	1.86	4.4	25.7	71.8	301.6
Mar 20 (Equinox)	11.9	2.27	5.3	49.9	139.6	713.5
Jun 21 (Solstice)	14.5	2.75	6.5	67.3	188.6	1169.1
Sep 22 (Equinox)	11.9	2.27	5.3	50.1	140.2	717.6
Dec 21 (Solstice)	9.5	1.81	4.3	22.9	64.0	261.7

2.3 Analytical Dose Computation

A critical advantage of the Gaussian model is that the total daily dose—the integral of irradiance over time—has an exact analytical solution:

$$D = A \cdot \sigma \cdot \sqrt{(2\pi)} \cdot 3600 \quad [J/m^2] \quad \text{(Eq. 3)}$$

where the factor of 3600 converts from W·h/m² to J/m². The dose accumulated within any time window $[t_1, t_2]$ is computed analytically using the standard normal cumulative distribution function Φ:

$$D(t_1, t_2) = D_{total} \cdot [\Phi((t_2 - \mu)/\sigma) - \Phi((t_1 - \mu)/\sigma)] \quad \text{(Eq. 4)}$$

This eliminates the need for numerical integration and provides exact dose calculations from just three measured or estimated parameters (A, μ, σ). It also enables direct computation of the dose fraction contained within any shade window, which is the foundation of the PWSF classification system described in Section 4.

2.4 The Dose Concept: Intensity × Time

The biological basis for cumulative dose assessment is well established in human photobiology. The Standard Erythemal Dose (SED), defined as 100 J/m² of erythemally-weighted UV radiation, is the internationally recognized unit for quantifying UV exposure. Research has demonstrated that reciprocity holds between dose rate and exposure time for erythemal response: the tissue-damaging effect of a high-intensity, short-duration exposure is equivalent to that of a proportionally lower-intensity, longer-duration exposure delivering the same total dose (McKinlay and Diffey, 1987; Meanwell and Diffey, 1989).

While plant-specific UV dose-response relationships are less extensively characterized than those for human skin, the underlying photochemistry is analogous. UV-B radiation (280–315 nm) damages plant DNA through the formation of cyclobutane pyrimidine dimers (CPDs), and UV-A (315–400 nm) generates reactive oxygen species that cause oxidative damage to cellular components. Both mechanisms are cumulative—total absorbed energy drives total damage. Plants have evolved repair mechanisms (photolyase enzymes, antioxidant systems), but these have finite capacity. When cumulative dose exceeds repair capacity, visible damage occurs. Native Mojave species have evolved enhanced UV protection (trichomes, reflective leaf surfaces, flavonoid accumulation), while imported horticultural species from lower-UV environments lack these adaptations and are therefore more susceptible to cumulative UV damage.

3. Three-Point Field Measurement Protocol

3.1 Rationale

If the diurnal UV irradiance curve is Gaussian, it is fully defined by three parameters: amplitude A, center μ, and width σ. Since μ (solar noon) is known for any date and location from astronomical calculations, only A and σ require field measurement. Three strategically timed UV readings provide sufficient data to determine both parameters and simultaneously validate the Gaussian assumption through internal consistency checks.

3.2 Measurement Timing

The three measurement points are:

Point 1 (Peak): Solar noon. This reading gives the amplitude A directly. For Las Vegas, solar noon ranges from 12:39 PM PDT (December) to 12:42 PM PDT (June).

Point 2 (1σ): One standard deviation before solar noon. The reading should equal 60.65% of the peak value ($e^{-2^{1}0.5}$). In summer, this falls at approximately 9:57 AM; in winter, at approximately 10:50 AM.

Point 3 (2σ): Two standard deviations before solar noon. The reading should equal 13.53% of the peak value (e^{-2}). In summer, this falls at approximately 7:12 AM; in winter, at approximately 9:01 AM.

3.3 Gaussian Validation

The internal consistency of the three measurements validates the Gaussian assumption without requiring additional data. Two ratios are computed:

$$R_1 = I(1\sigma) / I(peak) \quad \textit{Expected: } 0.6065 \pm 10\%$$

$$R_2 = I(2\sigma) / I(peak) \quad \textit{Expected: } 0.1353 \pm 20\%$$

If both ratios fall within their acceptable ranges, the Gaussian model is confirmed and the analytical dose formulas (Equations 3 and 4) yield exact results. If either ratio deviates beyond 25%, the day is flagged as non-Gaussian (due to cloud cover, unusual atmospheric conditions, or terrain effects), and additional measurement points or numerical integration are required.

3.4 Gaussian Parameter Recovery from Field Data

Given the peak measurement I(peak) at time t_0 and an off-peak measurement $I(t_1)$ at time t_1, the width parameter σ is recovered by inverting the Gaussian equation:

$$\sigma = |t_1 - t_0| / \sqrt{(-2 \cdot ln(I(t_1)/I(peak)))} \quad \text{(Eq. 5)}$$

This measured σ can be compared against the theoretical seasonal value from Equation 2 as an additional quality check. Significant deviations may indicate elevated aerosol loading, residual cloud effects, or atmospheric conditions warranting investigation.

3.5 Comparative Microclimate Measurement

To characterize a microclimate, the three-point protocol is executed simultaneously at two locations: a reference station in full, unobstructed sunlight and the microclimate site of interest. The ratio of microclimate to reference readings at each time point yields the shade transmission profile—the fraction of incident UV that reaches the plant through the shading features. This transmission profile, combined with the Gaussian dose model, enables computation of the Peak-Weighted Shade Factor.

4. Peak-Weighted Shade Factor (PWSF) Classification System

4.1 Definition

The Peak-Weighted Shade Factor (PWSF) quantifies the effective UV dose reduction provided by a microclimate's shading features, weighted by the timing of shade relative to the peak of the irradiance curve. For a shade window from t_1 to t_2 with opacity α (0 = transparent, 1 = fully opaque):

$$PWSF = \alpha \cdot [\Phi((t_2 - \mu)/\sigma) - \Phi((t_1 - \mu)/\sigma)] \quad \text{(Eq. 6)}$$

For multiple shade windows (e.g., a wall providing morning shade and a tree providing afternoon shade), PWSF values are additive:

$$PWSF_{total} = \Sigma\, \alpha_i \cdot [\Phi((t_{2i} - \mu)/\sigma) - \Phi((t_{1i} - \mu)/\sigma)] \quad \text{(Eq. 7)}$$

The PWSF captures a critical insight that simple percentage-shade metrics miss: the timing of shade matters as much as its duration. Because the irradiance curve is Gaussian, a shade window centered on solar noon blocks a disproportionately large fraction of the daily dose compared to an equal-duration window in the morning or afternoon. This is quantified by the standard normal CDF weighting in Equation 6.

4.2 Classification System

Based on the PWSF, we propose a six-tier microclimate classification system for desert horticulture (Table 2). Each class corresponds to a range of cumulative UV dose reduction and maps to specific plant group viability.

Table 2. PWSF Microclimate Classification System for Desert Horticulture.

Class	PWSF Range	Category	UV Dose Reduction	Suitable Plant Groups
MC-0	0.00–0.05	Full Exposure	< 5%	Native Mojave only: creosote, brittlebush, desert marigold
MC-1	0.05–0.15	Minimal Shade	5–15%	Native + UV-tolerant: prickly pear, agave, desert willow
MC-2	0.15–0.30	Light Shade	15–30%	Hardy adapted: lantana, oleander, Texas sage, pomegranate
MC-3	0.30–0.50	Moderate Shade	30–50%	Semi-shade tolerant: citrus, herbs, bougainvillea
MC-4	0.50–0.70	Heavy Shade	50–70%	Shade-preferring: vegetables, impatiens, ferns
MC-5	0.70–1.00	Deep Shade	70–100%	Shade-dependent: indoor plants outdoors, seedlings

4.3 Example Applications

Table 3 presents PWSF values for common Las Vegas residential shading scenarios on the summer solstice, demonstrating the classification system's ability to discriminate between microclimates that would appear similar under simple shade-percentage analysis.

Table 3. PWSF values for common residential shading scenarios, Summer Solstice, Las Vegas.

Shading Scenario	PWSF	Dose Red. (%)	Class	Category
No shade (full exposure)	0.000	0.0	MC-0	Full Exposure
Palm tree, 1-hour noon shadow	0.122	12.2	MC-1	Minimal
Palm tree, 2-hour noon shadow	0.240	24.0	MC-2	Light

Extended noon shade (10–14:00)	0.451	45.1	MC-3	Moderate
East wall, AM shade (6–10:00)	0.212	21.2	MC-2	Light
Patio cover (10–15:00)	0.524	52.4	MC-4	Heavy
Mesquite tree (9–15:00, 70% opacity)	0.505	50.5	MC-4	Heavy
Dense shade cloth, all day	0.830	83.0	MC-5	Deep

5. Discussion

5.1 The Timing Asymmetry

Perhaps the most significant finding of this analysis is the quantification of timing asymmetry in shade value. A four-hour shade window centered on solar noon (10:00–14:00) yields a PWSF of 0.451 and an MC-3 classification. By contrast, the same four hours of shade in the early morning (6:00–10:00) yields a PWSF of only 0.212 (MC-2). The midday shade blocks more than twice the cumulative UV dose of the morning shade. This has direct practical implications for garden design: a palm tree that casts its shadow at solar noon is quantifiably more valuable than a wall that provides shade only in the morning, even if the total shaded hours are identical.

5.2 Seasonal Variation in Shade Effectiveness

The narrower winter UV curve (σ = 1.81 hours vs. 2.75 hours in summer) means that the same shade window captures a larger fraction of the total daily dose in winter. A two-hour midday shade window blocks 24% of the summer daily dose but 36% of the winter daily dose. This has implications for plant selection in partially shaded microclimates: species that survive summer in MC-2 conditions may effectively experience MC-3 conditions in winter due to the narrower irradiance curve, potentially receiving insufficient UV for species that require some UV exposure for normal growth.

5.3 Implications for Desert Horticulture

The PWSF system provides, for the first time, a quantitative basis for matching plant species to specific microclimate conditions in desert environments. Current horticultural guidance categorizes shade in qualitative terms (“full sun,” “partial shade,” “full shade”) that were developed for temperate, humid climates where the distinction between sun and shade is primarily about visible light for photosynthesis. In the Mojave Desert, the critical variable is not visible light availability (which is rarely limiting even in shade) but cumulative UV dose, which drives tissue damage in non-adapted species. The widely observed phenomenon of “full sun” plants dying in Las Vegas gardens—despite receiving adequate water and nutrients—is consistent with cumulative UV dose exceeding the damage threshold of species evolved for lower-UV environments.

5.4 Relationship to Prior Work

This paper extends our prior findings on UV radiation as a primary factor in Las Vegas plant mortality (Brandys and Brandys, 2025) by providing the mathematical framework for quantifying UV dose in microclimates. It also integrates with our research on the optimal timing of irrigation (Brandys and Brandys, 2025), as the soil surface temperature component of that analysis is influenced by the same radiation profile modeled here.

6. Conclusions

This paper presents three integrated contributions to desert microclimate science:

First, diurnal UV irradiance under clear desert skies follows a Gaussian distribution with seasonally predictable parameters. The width parameter σ ranges from 1.81 hours (winter solstice) to 2.75 hours (summer solstice) at Las Vegas latitude, and is narrower than the corresponding total solar irradiance curve due to enhanced atmospheric attenuation of shorter wavelengths at low sun angles.

Second, the Gaussian model enables a practical three-point field measurement protocol. Three UV readings—at 2σ before noon, 1σ before noon, and at solar noon—fully characterize the daily UV dose curve and provide built-in validation of the Gaussian assumption through internal ratio checks.

Third, the Peak-Weighted Shade Factor (PWSF) provides the first quantitative metric for classifying desert microclimates based on cumulative UV dose reduction. The six-tier MC-0 through MC-5 classification maps specific shade configurations to quantified dose reductions and appropriate plant species, replacing the qualitative and climatically inappropriate shade categories currently in use.

The practical significance of this work lies in its direct applicability to desert garden design. By quantifying the dose reduction provided by specific shade features (trees, walls, structures) at specific times, the PWSF system enables gardeners and landscape designers to make evidence-based decisions about plant placement. The analytical framework is computationally simple, implementable in standard spreadsheet or database tools, and requires only a handheld UV meter and three strategically timed measurements to characterize any microclimate site.

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