Artificial Light at Night Erodes Cultural Ecosystem Services at Scale

Jordan W. Smith[1*], J. Adam Beeco[2], Sharolyn J. Anderson[2], Peter Tsigaris[3], Zachary D. Miller[1], Emily J. Wilkins[1], Anna B. Miller[1], Chase C. Lamborn[1], John C. Barentine[4]

[1]Utah State University, Logan, Utah, USA.
[2]U.S. National Park Service, Fort Collins, Colorado, USA.
[3]Thompson Rivers University, Kamloops, British Columbia, Canada.
[4]Dark Sky Consulting, LLC, Tucson, Arizona, USA.

*Corresponding author: jordan.smith@usu.edu

Summary

Artificial light at night (ALAN) is expanding rapidly, yet its implications for human well-being are rarely quantified in welfare terms. We develop a cultural ecosystem service accounting approach that links monitored night sky conditions to recreation behavior and monetary value. Using visitor-intercept surveys from designated dark sky parks across the Colorado Plateau, we estimate multi-site site choice models in which trip decisions respond to travel cost, meteorology, and two alternative night sky measures: the Anthropogenic Light Ratio (ALR) and a Bortle Dark Sky Index that more fully captures night sky viewing conditions. Visitors are less likely to choose parks with greater anthropogenic skyglow or poorer realized night sky conditions, and they exhibit positive willingness to pay for darker skies. Simulating small park-specific degradation shocks equal to 0.1 standard deviations of observed night sky conditions yields substantial aggregate welfare losses, concentrated in high-visitation parks. These results establish ALAN as a quantifiable externality and provide a transferable welfare accounting framework for incorporating night sky degradation into natural capital accounts, lighting policy, land-use planning, and benefit–cost evaluation.

Keywords: Artificial Light at Night, Cultural Ecosystem Services, Random Utility Model, Recreation Demand, Consumer Surplus, Natural Capital Accounting

1 Introduction

Artificial light at night (ALAN) is an expanding anthropogenic impact that is transforming nocturnal environments and the benefits people derive from them [1]. Satellite and ground-based observations indicate that light pollution has already made the Milky Way invisible to more than one-third of humanity and that night sky brightness continues to rise rapidly [2–4]. ALAN therefore represents a pervasive externality: the private benefits of illumination are localized, whereas ecological, public health, cultural, and energy-related costs diffuse across space, time, and jurisdictions [1]. Ecologically, ALAN disrupts biological rhythms and community interactions and can degrade ecosystem functions and services [5–8] while eroding the aesthetic and experiential qualities of nightscapes [9]. Exposure is linked to sleep and broader health outcomes [10], can be unevenly distributed, and may exacerbate environmental inequities [11]. Outdoor lighting also entails energy use and associated cost, linking ALAN to climate-mitigation and efficiency objectives [12, 13].

A central challenge for sustainability governance is that many of these costs remain unpriced and therefore underweighted in land-use and lighting decisions [1, 14, 15]. Night sky quality can be treated as a cultural ecosystem service (CES): a public-goods benefit jointly produced through interactions among protected landscapes, atmospheric conditions, and human perceptions and practices such as stargazing, awe, and place-based meaning [16–18]. The mechanisms by which ALAN erodes this CES can be organized using an ecosystem services cascade (Fig. 1), in which lighting alters the environmental state, changes service supply, shapes realized benefits, and ultimately reduces social value [19–21]. Bringing night sky quality into natural capital style accounting can therefore enable comparisons among safety, development, tourism, and conservation objectives, and make the external costs of lighting legible within benefit–cost deliberations [17, 18, 22].

Dark sky recreation emerges from the interaction of nocturnal environmental conditions (darkness and visibility shaped by skyglow, atmospheric clarity, and meteorology) and the social and institutional conditions that make dark sky experiences accessible and legible as a recreation product [16–18]. Drivers such as population growth, transportation infrastructure, and other artificial light sources generate pressures through the intensity, spectrum, timing, and spatial distribution of emissions [24], and global syntheses show that skyglow increasingly affects rural and protected landscapes [2, 3]. Satellite mega-constellations pose additional threats to night sky visibility [25–27]. As darkness becomes more scarce, demand for destination branding around nightscape quality has grown [14, 28]. Yet a core governance complication is spatial spillover: atmospheric scattering propagates light over long distances, making protected areas vulnerable even when on-site lighting is well managed [2, 3, 24], and meteorological conditions such as cloud cover can further increase observed brightness and expand the footprint of light pollution [29, 30].

The nocturnal environmental state can be monitored using satellite nighttime radiance and complementary proxies for viewing conditions, along with temporal covariates such as lunar illumination and seasonality [2, 29, 31]. Long-term evidence that night sky brightness is worsening [3, 4] highlights a decision gap: monitoring indicates exposure to ALAN, but not the welfare consequences needed to evaluate

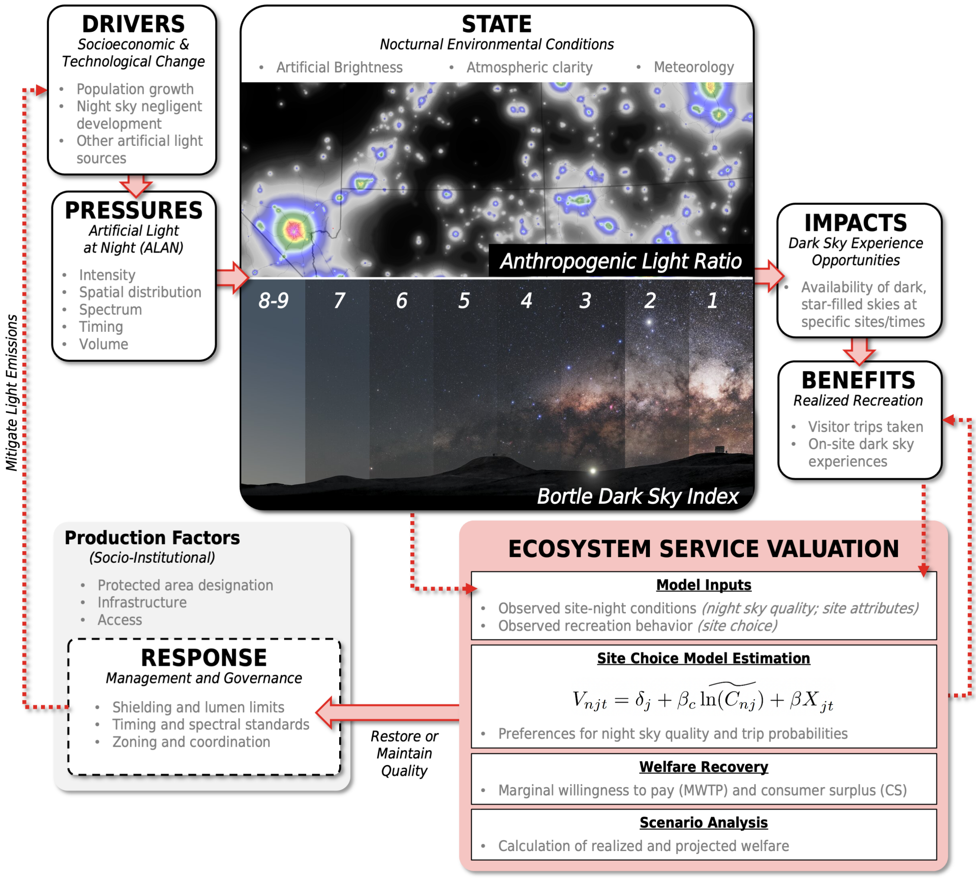

Fig. 1 Conceptual framework for valuing dark sky cultural ecosystem services given growing artificial light at night (ALAN). Socioeconomic and technological drivers generate ALAN pressures, which alter the nocturnal environmental state through changes in artificial brightness, atmospheric clarity, and meteorological conditions. Two complementary state indicators are shown: the Anthropogenic Light Ratio (the artificial component of all-sky brightness) and the Bortle Dark Sky Index (realized night sky viewing quality on an easily interpretable 1–9 scale). Changes in state produce impacts, defined here as dark sky experience opportunities, and subsequently benefits, expressed as realized recreation through visitor trips and on-site dark sky experiences. The lower panel shows the study's valuation workflow: observed site-night conditions and observed recreation behavior are combined in a site choice model to recover preferences, trip probabilities, marginal willingness to pay (MWTP), and consumer surplus (CS), which then support scenario analysis and estimates of realized and projected welfare. Production factors such as protected area designation, infrastructure, and access condition the realization of dark sky benefits, while management responses including shielding, lumen limits, timing controls, and zoning/coordination can mitigate emissions and help restore or maintain night sky quality. The framework is intended to support sustainability governance by translating monitored environmental change into welfare metrics that can be compared with the costs of lighting mitigation and land-use decisions. Visualization of ALR from Falchi et al. [2] and image of the Bortle Dark Sky Index courtesy of the European Southern Observatory [23].

development, infrastructure, or conservation choices [19, 22]. Research in protected areas indicates that night skies are an explicit part of the recreation experience and that some visitors would reduce visitation if stargazing quality deteriorated [28]. Designations and interpretive programming can increase awareness and demand [32], but multi-site evidence also highlights tensions between nighttime safety and conserving darkness, implying that CES protection depends on governance choices rather than monitoring alone [28]. Existing economic valuations remain limited. Stated preference studies find positive willingness to pay for preserving or improving night sky visibility [33], while economic impact studies quantify spending, jobs, and income associated with astrotourism [34]. Neither provides a revealed preference welfare metric directly suited to externality accounting and benefit–cost comparison [35–37].

Our primary revealed preference analysis focuses on visitors participating in dark sky dependent recreation activities because these are the individuals for whom a behavioral link between trip choice and night sky quality is most defensible. For these visitors, the quality of the nocturnal environment is part of the recreation product itself. By contrast, visitors engaged in non-dark sky dependent activities may still prefer darker skies, but their trips are not defined by direct dependence on night sky visibility. We therefore treat dark sky dependent recreationists as the main welfare-accounting population and estimate parallel models for non-dark sky dependent visitors as an ancillary robustness test.

This study advances an externality-oriented valuation agenda for ALAN in three ways. First, we estimate recreational welfare attributable to dark, clear night skies using multi-site random utility (site choice) models parameterized with on-site visitor survey data from designated dark sky parks across the Colorado Plateau (Fig. 2), integrating satellite-based brightness measures, night sky clarity proxies, meteorology, and site controls. Second, we translate the estimated site choice relationships into marginal willingness to pay for changes in night sky and meteorological conditions. Third, we conduct an ex-ante scenario analysis, consistent with documented contemporary growth in brightness [3, 4], to translate plausible ALAN-driven degradation into projected welfare losses and a monetary indicator of CES value at risk.

2 Results

2.1 Survey Response and Characteristics of Dark Sky Dependent Recreationists

Nearly two-thirds (61.8%) of surveyed visitors reported participating in at least one dark sky dependent activity—night sky viewing/astronomy, night sky photography, and/or nighttime wildlife observation—during their trip (Supplementary Information, Table S1). Night sky viewing/astronomy dominated participation (91.0% of dark sky recreationists), with smaller but still meaningful shares reporting night sky photography (24.2%) and nighttime wildlife observation (22.7%), indicating that many visitors engaged in multiple nocturnal activities. Dark sky recreation on the Colorado Plateau was primarily an overnight experience: 95.9% reported an overnight trip averaging 4.2 days, and travel distances were substantial (mean = 949.6 miles; 879.9 minutes). Awareness of *DarkSky International* certification was notable (46.6%).

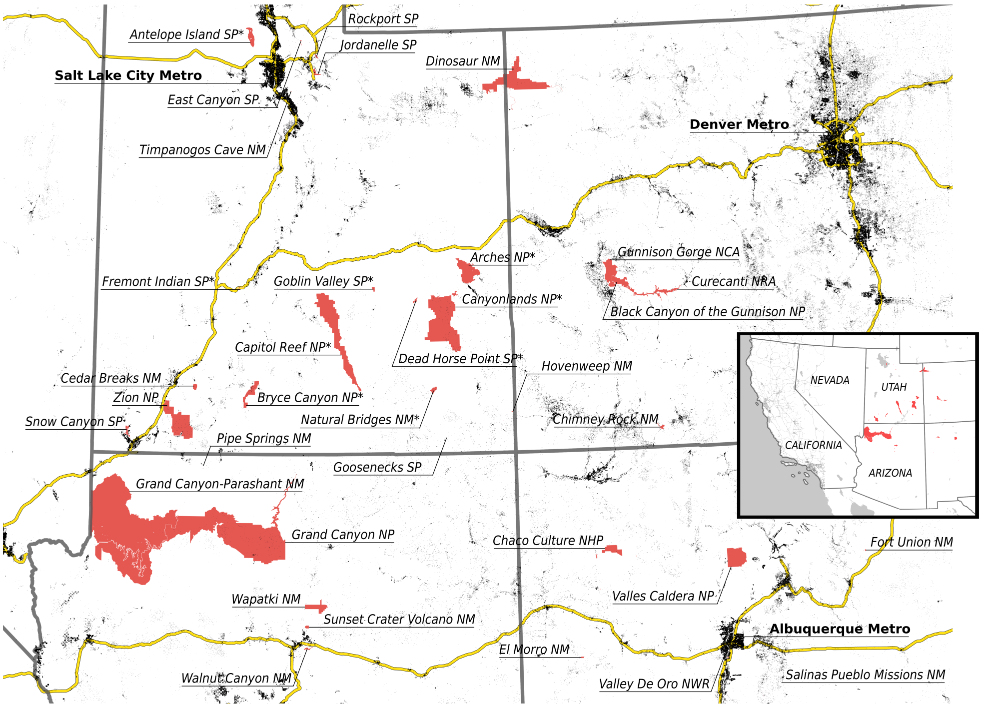

Fig. 2 Designated dark sky parks within the Colorado Plateau (as of 2022). All 36 park units that comprised the study's choice set are shown. Park units where the on-site visitor surveys were conducted are denoted with an asterisk. Populated areas visualized in black [38]. Yellow lines are interstate highways.

Sociodemographically, respondents participating in dark sky dependent activities were, on average, 47.5 years old; 52.2% identified as male and 46.7% as female; most held at least a bachelor's degree (79.8%); about half reported household incomes $\geq$ \$100,000 (50.8%); and 95.7% identified as White (Supplementary Information, Table S1).

2.2 Anthropogenic Light and Dark Sky Visibility

We characterized night sky conditions using two complementary measures: the calibrated mean all-sky Anthropogenic Light Ratio (ALR), which isolates the artificial component of average all-sky luminance, and the park- and night-specific Bortle Dark Sky Index, which integrates anthropogenic skyglow with moonlight, atmospheric attenuation, and cloud-related visibility constraints [39]. Because the Bortle Dark Sky Index incorporates both anthropogenic and non-anthropogenic drivers of visibility, it should be interpreted as a measure of realized night-sky experience rather than as a pure skyglow metric. A summary of the distribution of nightly Bortle values across parks is provided in the Supplementary Information (Figure S2).

Across the 36-site choice set, most park units exhibited generally dark conditions over the study period, but with clear variation across sites in both typical conditions and temporal stability (Fig. 3). The darkest and most consistently favorable conditions were concentrated in remote units such as Natural Bridges National Monument, Goosenecks State Park, Capitol Reef National Park, Hovenweep National Monument, Goblin Valley State Park, and Canyonlands National Park, all of which had mean Bortle values near 2.3–2.4 and mean ALR values of roughly 0.05–0.13. By contrast, urban-proximate sites exhibited notably brighter conditions. The highest mean Bortle values occurred at Jordanelle State Park (5.25), Valle de Oro National Wildlife Refuge (4.91), and Timpanogos Cave National Monument (4.15), while the largest mean ALR values occurred at Valle de Oro National Wildlife Refuge (22.17), Timpanogos Cave National Monument (13.07), and Snow Canyon State Park (4.70).

Figure 3 also reveals substantial temporal structure. Bortle values fluctuate within sites across the study period, reflecting the combined influence of moon phase, cloudiness, and atmospheric attenuation on realized visibility. Superimposed ALR traces are comparatively stable within sites, especially at the darkest parks, but become both higher and more variable at several brighter locations. This distinction is especially visible at sites such as Natural Bridges National Monument and Goosenecks State Park, where ALR remains very low but Bortle values still fluctuate, versus sites such as Valle de Oro National Wildlife Refuge, Timpanogos Cave National Monument, and Jordanelle State Park, where high baseline ALR and consistently elevated Bortle values indicate chronically degraded night sky conditions.

Taken together, these patterns show that the study system is dominated by relatively dark parks, but that meaningful heterogeneity exists in both anthropogenic skyglow and realized viewing quality. Some parks provide consistently high-quality night conditions because both ALR and the Bortle Dark Sky Index remain low, whereas others experience chronically brighter skies or sharper episodic degradation. This variation provides the behavioral signal linking park-night choice to both the underlying artificial light environment and the realized quality of the nocturnal experience.

2.3 Preferences and Marginal Values

Estimated preferences are directionally consistent with theory across the final site choice specifications (Fig. 4 and Supplementary Information, Table S2). Travel cost enters negatively and is highly statistically significant in every model, indicating that respondents are less likely to choose parks that are more expensive to reach. In the ALR specification, the coefficient on log travel cost is -2.726 ($p < 0.001$); in the Bortle specification with residuals, it is -2.692 ($p < 0.001$). Respondents also preferred warmer nighttime conditions and avoided precipitation and wind. In the ALR model, minimum temperature is positive and significant (coef. = 0.849, $p < 0.001$), while precipitation (coef. = -1.181, $p < 0.001$) and wind speed (coef. = -0.513, $p = 0.003$) reduce the likelihood of site choice. The same qualitative pattern holds in the Bortle specification with residuals, where minimum temperature remains positive (coef. = 1.029, $p < 0.001$), precipitation negative (coef. = -1.091, $p < 0.001$), and wind speed negative (coef. = -0.670, $p < 0.001$).

Night sky conditions are also strongly related to site choice. In the ALR specification, greater anthropogenic skyglow reduces the probability of choosing a site (coef. =

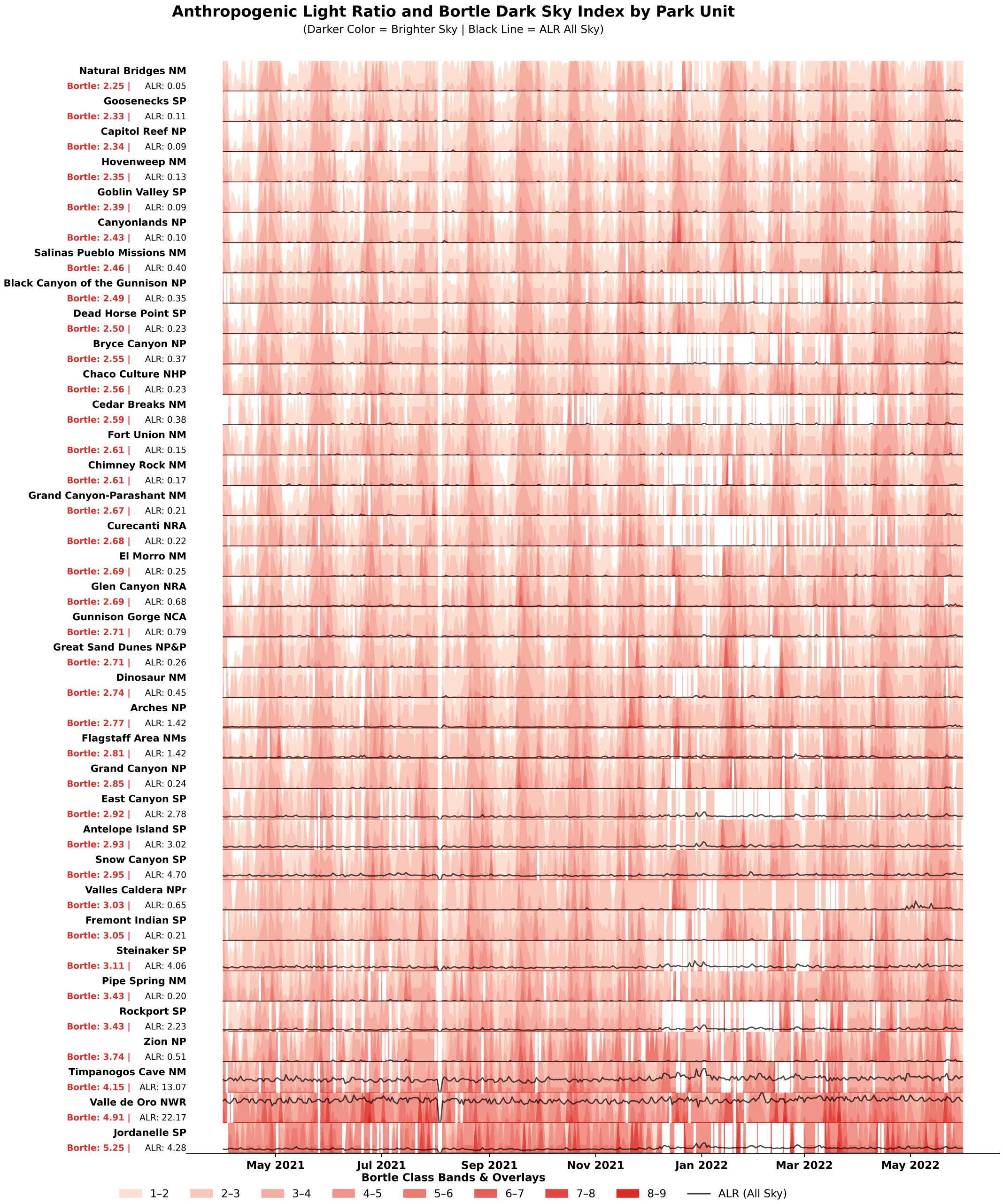

Fig. 3 Spatiotemporal variation in night sky brightness across 36 park units. The figure shows the nightly Bortle Dark Sky Index from April 2021 to May 2022, ordered vertically by mean Bortle value (darkest/best sites at top). Shading indicates nightly Bortle class bands, with darker red tones corresponding to higher Bortle values (brighter and poorer viewing conditions). The overlaid black line shows the calibrated mean all-sky Anthropogenic Light Ratio (ALR) for each site. Together, the two measures distinguish persistent anthropogenic skyglow from nightly experiential variation driven by moonlight, clouds, and atmospheric attenuation.

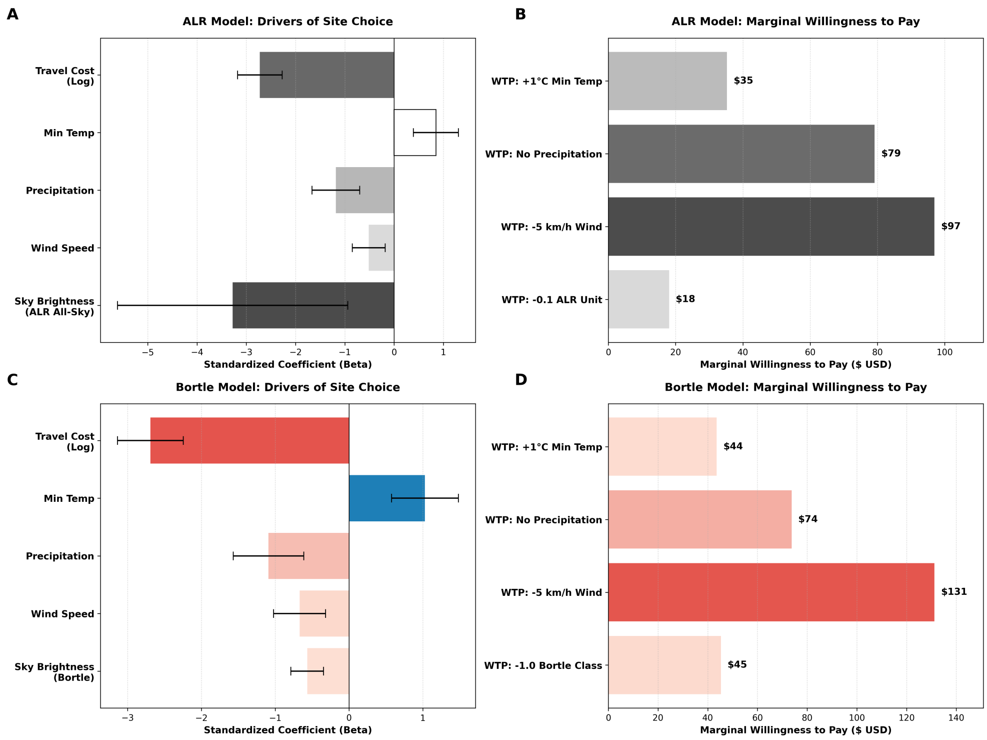

Fig. 4 Estimated drivers of site choice and implied marginal willingness to pay under the ALR and Bortle specifications. Panels **A** and **C** report standardized coefficients from the final conditional logit site choice models for dark sky dependent recreationists. In both specifications, higher travel cost, precipitation, wind speed, and poorer dark sky conditions reduce the probability of site choice, whereas warmer minimum nighttime temperatures increase it. Panel **A** shows results from the model using the calibrated mean all-sky Anthropogenic Light Ratio (ALR) as the dark sky state indicator. Panel **C** shows the parallel model using the Bortle Dark Sky Index. Error bars indicate 95% confidence intervals around the standardized coefficient estimates. Panels **B** and **D** translate these estimates into marginal willingness to pay (MWTP) for improvements in nighttime environmental conditions. Under the ALR specification (**B**), respondents are willing to pay approximately \$35 per trip for a +1°C increase in minimum temperature, \$79 to avoid precipitation, \$97 for a 5 $\mathrm{km\,h^{-1}}$ reduction in wind speed, and \$18 for a 0.1-unit reduction in calibrated mean all-sky ALR. Under the Bortle specification (**D**), the corresponding values are approximately \$44 for a +1°C increase in minimum temperature, \$74 to avoid precipitation, \$131 for a 5 $\mathrm{km\,h^{-1}}$ reduction in wind speed, and \$45 for a one-class improvement (darker/better) in the Bortle Dark Sky Index. Together, the panels show that both anthropogenic skyglow and broader realized night sky conditions are economically meaningful determinants of recreation behavior.

-3.273, $p = 0.006$). In the Bortle specification with residuals, worse realized night sky conditions similarly reduce site choice probability (coef. $= -0.567$, $p < 0.001$). The residual diagnostics show that moonlight and atmospheric moisture retain explanatory power beyond the composite index: the lunar irradiance residual is negative and highly significant (coef. $= -1.475$, $p < 0.001$), as is the humidity residual (coef. $= -1.052$, $p < 0.001$). By contrast, the skyglow residual is negative but not statistically significant (coef. = -0.092, $p = 0.553$), suggesting that the anthropogenic light signal is largely absorbed by the composite index itself. The residualized Bortle specification also provides the best fit (Supplementary Information, Table S2), with a log-likelihood of -526.35, compared to -538.10 for the ALR model and -545.36 for the simpler meteorological + Bortle model. A supplementary analysis fit to non-dark sky dependent recreationists yields the same directional relationship between site choice and darker skies (Supplementary Information, Table S3), indicating that the main findings are not unique to explicitly dark sky oriented visitors, even though the primary welfare analysis appropriately focuses on the dark sky dependent subsample. A comparison of per-trip consumer surplus across visitor types is reported in the Supplementary Information (Table S4).

These preference estimates translate into meaningful marginal willingness to pay (MWTP) for improvements in nighttime environmental conditions (Fig. 4). In the ALR specification, respondents are willing to pay approximately \$35 per trip for a +1°C increase in minimum temperature, \$79 to avoid precipitation, \$97 for a 5 km/h reduction in wind speed, and \$18 for a 0.1-unit reduction in calibrated mean all-sky ALR. In the Bortle specification, the corresponding values are approximately \$44 for a +1°C increase in minimum temperature, \$74 to avoid precipitation, \$131 for a 5 km/h reduction in wind speed, and \$45 for a one-class improvement in the Bortle Dark Sky Index. Across both specifications, respondents place substantial value on improved night conditions, but the night sky measures are not valued in isolation from weather. The large MWTP for avoiding wind and precipitation shows that the realization of dark sky CES depends jointly on darkness, visibility, and nighttime comfort, while the positive willingness to pay for lower ALR and lower Bortle class confirms that darker skies generate meaningful welfare gains for dark sky dependent recreationists.

2.4 Welfare at Risk

Applying park-specific degradation shocks equal to 0.1 standard deviations of each park's observed night-sky metric, we estimate substantial welfare losses under both night sky specifications (Fig. 5). Summed across the sampled months of April, May, September, and October 2021, the Bortle-based specification yields total aggregate welfare losses ranging from approximately \$25.3 million under the high re-entry assumption to \$65.5 million under the low re-entry assumption, while the ALR-based specification yields total losses ranging from approximately \$23.0 million to \$58.3 million. Although the two specifications produce somewhat different loss magnitudes at particular parks, both show that aggregate welfare at risk is concentrated in a relatively small number of high-visitation destinations, indicating that regional losses are driven primarily by the interaction of visitor volume and the estimated sensitivity of site choice to degraded night sky conditions.

The largest absolute losses occur at flagship parks. Grand Canyon National Park and Zion National Park exhibit the largest modeled losses under both specifications, followed by Arches National Park, Bryce Canyon National Park, Dead Horse Point State Park, and Capitol Reef National Park. At the lower end of the distribution, many smaller or more remote parks exhibit comparatively modest aggregate losses. This pattern reflects lower visitation volumes rather than an absence of value.

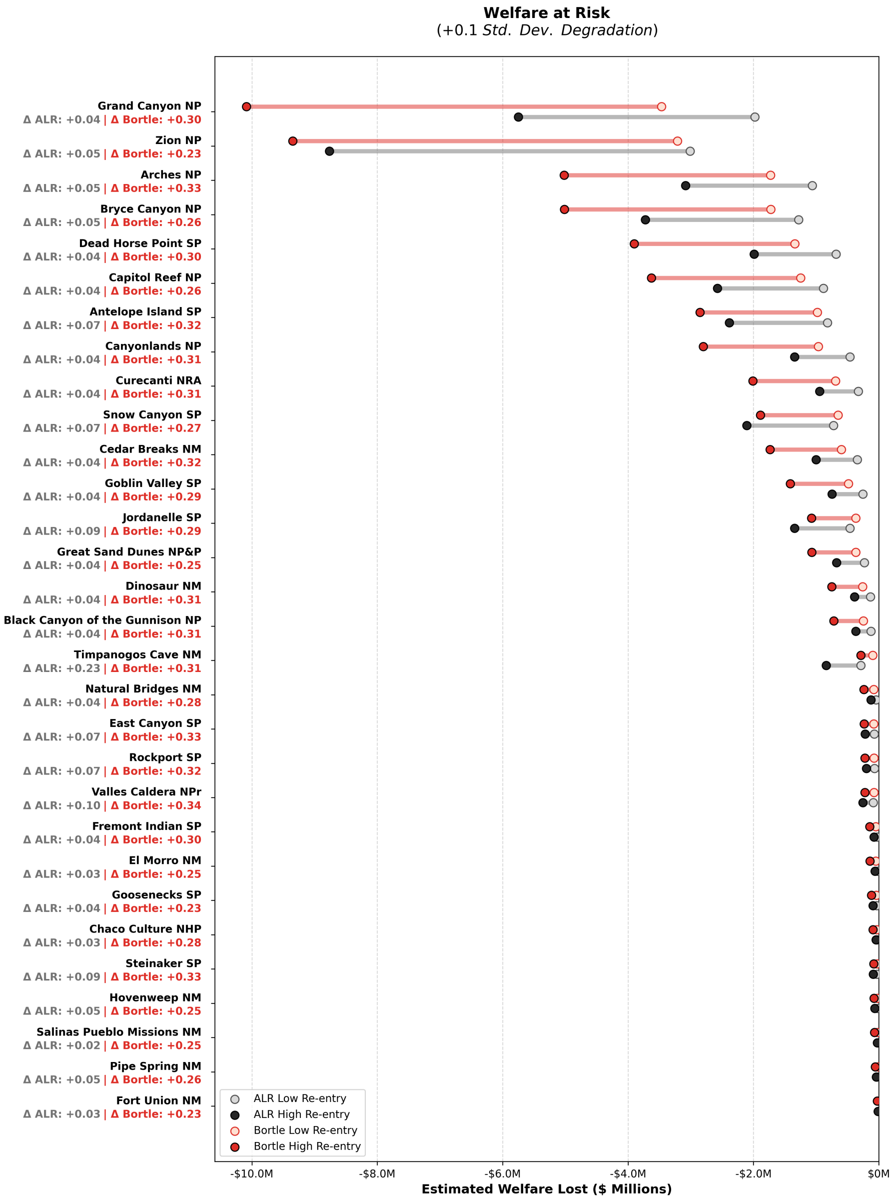

Fig. 5 Aggregate welfare at risk under night sky degradation. The figure shows the estimated range of aggregate welfare losses across park units during the sampled months of April, May, September, and October 2021 under two alternative night sky specifications: the calibrated mean all-sky Anthropogenic Light Ratio (ALR; gray) and the Bortle Dark Sky Index (red). For each park, the degradation scenario is defined as a positive shock equal to 0.1 standard deviations of that park's observed distribution for the relevant metric; the corresponding shock magnitudes are reported at left as ΔALR and ΔBortle. For each specification, lower- and upper-bound estimates reflect alternative assumptions about unique visitors derived from re-entry rates of 3.2 and 1.1 visits per visitor, respectively. Larger negative values indicate greater modeled welfare loss. Welfare losses are concentrated in a relatively small number of high-visitation parks, but the relative magnitudes differ across specifications, with the largest losses occurring at flagship destinations such as Grand Canyon National Park, Zion National Park, Arches National Park, and Bryce Canyon National Park.

Figure 5 shows that the ALR and Bortle specifications yield relatively similar park-specific shock magnitudes, with the ALR specification yielding shocks that are slightly higher at urban-adjacent or already bright parks. For example, the ALR specification yields comparatively larger losses at sites such as Timpanogos Cave National Monument, Jordanelle State Park, and Snow Canyon State Park, while the Bortle specification remains comparatively larger at several flagship dark sky destinations. Taken together, the results show that even modest, park-specific degradations in night sky conditions can produce sizable and spatially uneven welfare losses, with the greatest absolute risks concentrated in high-demand parks.

3 Discussion

This study reframes ALAN as a monetizable externality that erodes non-market welfare generated by protected landscapes at night. Using revealed preference behavior across a multi-site system of designated dark sky parks, we show that visitors' trip choices are systematically responsive to realized night sky quality, and that even modest degradation scenarios translate into large welfare losses when scaled through visitation. Lighting decisions that increase regional skyglow therefore impose measurable costs on recreationists who travel to experience natural darkness.

A key implication of the MWTP and welfare at risk results is that dark sky recreation is not a marginal amenity; it is a high-value experience for a behaviorally defined group of users whose focal activities require darkness and night-sky visibility. The estimated willingness to pay for darker skies is consistent with the notion that high-quality night skies are increasingly scarce and destinationized, generating demand that can be displaced or diminished as skyglow rises. Welfare losses are not evenly distributed. Aggregate losses concentrate in high-demand parks because small per-person welfare changes scale through large volumes of visitation. At the same time, the comparison between the ALR and Bortle specifications shows that estimated damages can differ materially across sites depending on whether degradation is represented as a change in anthropogenic skyglow alone or as a broader decline in realized night sky experience. This heterogeneity reflects baseline exposure, behavioral sensitivity to state change, and the scale of visitation.

The preference structure from the site choice model clarifies the production function of dark sky welfare. Visitors prefer lower travel costs, better night sky visibility, and more favorable nighttime conditions, implying that realized welfare is produced through the interaction of anthropogenic skyglow, atmospheric constraints, and the institutional context that makes dark sky experiences accessible and legible as a recreation product. This is consequential for policy design. First, skyglow is not merely a background condition; it is a state variable that shifts trip-taking probabilities and welfare flows in predictable directions. Second, meteorology and comfort act as binding constraints on whether the service is realized on a given park-night. Even in otherwise dark regions, unfavorable conditions reduce engagement in nocturnal activities and therefore reduce realized benefits. The supplementary models estimated for non-dark sky dependent recreationists also show the same directional preference for darker conditions, suggesting that the behavioral relevance of night sky quality extends beyond visitors whose trips are explicitly organized around dark sky dependent activities, even if the strongest welfare interpretation remains tied to that focal subsample.

Relative to prior work, our contribution is to move from stated preference estimates of willingness to pay and local economic impact assessments of astrotourism spending toward a revealed preference welfare metric directly comparable to policy costs. Stated preference studies demonstrate broad support for protecting dark skies, but their magnitudes can be sensitive to scenario framing and hypothetical bias [33]. Economic impact studies capture expenditures and jobs, but those measures are not net benefits and can overstate welfare when substitution and displacement are ignored [34]. By linking observed park-night variation in night sky conditions to site choice across a system of parks, our approach creates a bridge from monitoring to welfare accounting in which incremental degradation can be expressed in monetary damages.

The policy relevance of these estimates lies in their ability to compare the benefits of ALAN mitigation with the costs of lighting retrofits, ordinances, and cross-boundary governance. Because skyglow propagates across space, the pressures driving welfare losses are often external to park boundaries, meaning protected areas cannot manage the externality alone. Although in-park retrofits and visitor-facing practices can reduce local contributions and improve experience quality at specific locations, the welfare at risk results underscore the importance of cross-jurisdictional mitigation in gateway communities and transportation corridors where pressures are generated [40]. Policy responses range from lighting retrofits and ordinances to inter-jurisdictional coordination and formal designation programs [8]. The relevant response set includes shielding and directionality requirements, lumen caps, timing controls, and spectrum guidance, alongside coordinated planning instruments that recognize welfare damages accrue across the full market of visitors traveling to dark sky places for unique experiences [15, 40–42].

More broadly, the findings show how cultural ecosystem services can be made visible in sustainability decisions. Night sky quality is relational, experiential, and culturally meaningful, but it is also affected by measurable environmental pressures and produces behavioral responses that can be valued in welfare terms. This makes dark skies an instructive case for integrating cultural ecosystem services into natural capital accounting while retaining attention to the social and institutional conditions through which benefits are realized.

Several limitations are worth noting. First, welfare-loss aggregation is restricted to the four months aligned with the intercept sampling window (April, May, September, October). This improves internal consistency but limits inference about summer conditions, winter viewing, or annual damages. Second, the Bortle Dark Sky Index combines satellite-based radiance with atmospheric viewing proxies. This is scalable and policy-relevant, but it does not capture all perceptual dimensions of nightscapes, so measurement error may attenuate estimated preferences for sky quality; if anything, revealed welfare sensitivity may be conservative because satellite data can underestimate blue/white light. Third, the conditional logit specification assumes homogeneous preferences and independence of irrelevant alternatives. While sequential model building and information-criterion selection support parsimony and fit, unmodeled heterogeneity could affect MWTP magnitudes and substitution patterns among close alternatives. Fourth, aggregation from per-person welfare changes to monthly park-level losses relies on administrative visitation totals and an assumed share of visitors engaged in dark sky dependent activities; deviations in that share across sites and seasons can affect aggregate welfare-loss magnitudes.

The results motivate several next steps that would strengthen externality accounting and decision support. A large-scale validation effort pairing remote sensing with ground-based photometry, such as those collected as part of the U.S. National Park Service's monitoring efforts [43–45], could improve the use of the Bortle Dark Sky Index as a reliable indicator of dark sky viewing experiences. Extending the park-night environmental panel and the park-month welfare accounting to a full year, and repeating the analysis across multiple years, would enable annualized natural capital style accounts of dark sky welfare flows and damages under alternative growth and mitigation pathways. Modeling preference heterogeneity would better quantify distributional impacts and substitution across a system of sites. Finally, moving from uniform degradation to policy-counterfactual scenarios would enable benefit–cost ratios that directly inform ordinances, infrastructure investment, and cross-jurisdictional compacts.

In sum, this paper provides a defensible empirical bridge from ALAN-driven changes in the nocturnal environment to monetized welfare damages borne by park visitors. That bridge is the key contribution for positioning light pollution as an externality of current growth and development patterns: it makes the costs of incremental degradation legible, comparable, and actionable within the governance frameworks that already shape nighttime lighting and land-use decisions.

3.1 Conclusion

This study quantifies how incremental degradation in night sky conditions reduces the non-market welfare generated by protected landscapes at night. Using multi-site site choice models parameterized with on-site visitor surveys and linked to park-night measures of anthropogenic skyglow, atmospheric viewing conditions, and meteorology, we show that dark sky dependent recreationists sort across parks in response to realized night sky quality. Darker, clearer skies increase site choice probabilities, while higher travel costs and adverse nighttime weather reduce them, indicating that night sky conditions are economically meaningful state variables rather than passive background attributes.

Translating these behavioral relationships into monetary terms yields decision-relevant welfare metrics. The MWTP estimates show that visitors value both darker skies and favorable nighttime conditions, while the aggregate scenario analysis indicates that even modest degradation can generate substantial and spatially uneven welfare losses when scaled through visitation. Those losses are concentrated in high-demand parks, but their distribution also depends on whether degradation is represented as a change in anthropogenic skyglow alone or as a broader deterioration in realized night sky experience.

More broadly, the analysis provides a defensible empirical bridge from ALAN-driven environmental change to monetized cultural ecosystem service losses. By making the costs of incremental degradation legible in welfare terms, the study provides a foundation for incorporating night sky quality into natural capital accounting, lighting policy, and land-use decision making.

4 Methods

4.1 The Night Skies of the Colorado Plateau

The Colorado Plateau's dark skies are exceptional given the region's large, high-elevation, arid protected landscapes coincide with relatively sparse development, producing low regional skyglow and frequent high quality viewing conditions. Many national and state parks across the Plateau are explicitly managed for natural darkness (e.g., Natural Bridges' "primordial dark sky" management approach), reflecting both biophysical suitability and active stewardship [28]. Consistent with this setting, the Plateau contains one of the world's densest clusters of *DarkSky International* certified parks, monuments, reserves, and communities. The sites where the study's visitor intercept surveys took place included Arches, Bryce Canyon, Canyonlands, and Capitol Reef National Parks; Natural Bridges National Monument; and Antelope Island, Dead Horse Point, Fremont Indian, and Goblin Valley State Parks. Although the empirical application focuses on the Colorado Plateau, the framework is transferable to any region where spatially explicit night-sky indicators, recreation-demand data, and visitation records can be linked.

4.2 Data Collection

Survey Data Collection. Between April 1, 2021 and May 31, 2022, we conducted intercept visitor surveys at nine park units on the Colorado Plateau (four Utah state parks, four national parks, and Natural Bridges National Monument). The survey instrument contained questions related to activity participation, awareness of *DarkSky International* designation, other parks visited on the trip, and other topics (see Smith et al. [46] for the full survey instrument). The survey instrument was developed by the research team in consultation with the U.S. National Park Service's Natural Sounds and Night Skies Division and the Utah Division of State Parks. Sampling occurred on 82 site-nights, distributed across weekdays/weekends and across state/federal units, with occasional rescheduling for weather and technician availability. Trained technicians approached visitor groups at campgrounds, overlooks, roadside pull-offs, and parking areas from one hour before sunset to two hours after sunset ($\approx$ 3-hour shifts), targeting recreationists experiencing nighttime conditions. Visitors were surveyed only during April, May, September, and October because sunset times were too late during summer months to survey visitors for two hours after sunset (some parks in our sample closed at 10 pm). One adult per group (most recent birthday) was invited to participate. Surveys were administered on iPads using Qualtrics (OMB Control No. 1024-0224); screens were set to minimum brightness. In total, 776 contacts yielded 634 completed surveys (81.7% response rate). For the primary site choice and welfare analysis, we restrict the estimation sample to respondents who reported participation in a dark sky dependent recreation activity. This restriction is logical as the objective is to estimate welfare effects for visitors whose recreation choices can be logically linked to variation in night sky quality. Respondents engaged in other forms of recreation may also value darker skies, but for those visitors night sky quality is more plausibly an ancillary amenity than a defining trip attribute. To assess whether darker skies nonetheless matter for those visitors, we also estimate the same model structure for the non-dark sky dependent subsample as a supplementary analysis (reported below). Full details on the survey effort, including the survey instrument, can be found in Smith et al. [46].

Meteorological Data Collection. We characterized night sky viewing conditions and weather preferences using daily meteorological covariates matched to each site-date. For each study site (point location), we queried the nearest available weather-station time series using the Meteostat Python library [47] and retrieved daily measurements for minimum air temperature ($t_{\min}$, °C), total precipitation (precip, mm), and average wind speed (wspd, $\mathrm{km\,hr^{-1}}$) over the study period. These variables capture key components of thermal comfort and the feasibility/pleasantness of extended nighttime recreational activity and are also widely available at a daily resolution, which facilitates integration with satellite-based night sky measures.

Daily series occasionally contain gaps (e.g., due to station outages). To preserve a balanced panel for site choice estimation, we applied conservative gap handling: short gaps were interpolated when supported by adjacent observations and remaining missing values were imputed using site-specific seasonal means (computed over observed records at that site) [48]. All meteorological covariates were subsequently temporally-aligned to the trip date used in the site choice model (described below), ensuring that each alternative in each respondent's choice set had a complete vector of daily conditions.

Satellite Data Collection. We derived a calibrated park-specific nightly Anthropogenic Light Ratio (ALR) from the VIIRS Day/Night Band data (available as part of NASA's Black Marble product VNP46A2) following the simplified neighborhood-sum framework of Duriscoe et al. [49]. For each park-night, we extracted the VNP46A2 gap-filled BRDF-corrected nighttime lights layer and reprojected it to an equal-area grid so that annular neighborhood sums were area-consistent. We then summarized upward radiance within concentric distance bands extending 300 km from each park, applying a distance-decay weighting scheme, in which more distant sources contribute progressively less to predicted skyglow. Very low radiance values ($< 0.5\ \mathrm{nW\,cm^{-2}\,sr^{-1}}$) were set to zero to suppress background noise [49]. The resulting weighted radiance sums were calibrated against ground-based ALR observations from the U.S. National Park Service all-sky camera system using an origin-constrained linear regression, yielding a park-night ALR metric that estimates the artificial component of average all-sky luminance as a ratio to natural background (Supplementary Information, Figure S1, Panel A). We treat the calibrated ALR as an established anthropogenic skyglow indicator distinct from the broader Bortle-aligned index developed for this study.

Nighttime brightness and related atmospheric viewing proxies were assembled from satellite/reanalysis products accessed through Google Earth Engine. The core sky brightness measure was also obtained from NASA's Black Marble product VNP46A2 [50, 51]. From each daily image, we extracted the gap-filled BRDF-corrected nighttime lights layer (a radiance-based indicator of upward artificial emissions contributing to skyglow), as well as ancillary layers used to screen or characterize retrieval conditions (i.e., mandatory quality flag, snow flag, and cloud mask quality information).

Because perceived night sky quality is produced by both anthropogenic skyglow and contemporaneous atmospheric transparency, we complemented Black Marble with two additional remotely sensed proxies sampled at each site-date: aerosol optical thickness (AOT) at 550 nm from MERRA-2 aerosol diagnostics (total extinction AOT) [52–54]; and near-surface humidity conditions derived from ERA5 hourly temperature and dewpoint [55, 56]. MERRA-2 provides globally consistent, time-resolved aerosol diagnostics suitable for representing haze and particulate loading that reduces star visibility. ERA5 provides hourly reanalysis fields that enable construction of humidity-based transparency proxies.

Operationally, we sampled all data at the study site and aggregated to a nightly window designed to represent typical dark sky viewing conditions (rather than daytime conditions). For ERA5, we derived relative humidity (RH) from temperature and dewpoint using a standard Magnus-type formulation, then averaged RH over the nightly window. For MERRA-2, we averaged AOT over the same window. These satellite/reanalysis measures were then merged with the daily Black Marble observations by site and date to form a unified "night sky conditions" table used in index construction (see *Night Sky Quality/Bortle Scale Proxy Construction* section) and as alternative attributes in the site choice model (see *Site Choice Model* section).

4.3 Bortle Dark Sky Index Construction

To operationalize night sky quality in a form suitable for econometric analysis while preserving interpretability for managers and practitioners, we constructed a Bortle Dark Sky Index from satellite- and reanalysis-based nightly conditions. The index represents the effective viewing conditions on a specific park-night after accounting for skyglow, moonlight, atmospheric attenuation, and cloudiness, and it is the measure used in the site choice and welfare models.

The index is intentionally *Bortle-like* rather than a literal Sky Quality Meter reading. Its purpose is to translate remotely sensed and modeled drivers of night sky visibility into a continuous 1–9 scale that preserves the directional logic of the Bortle Dark Sky Scale, where lower values indicate darker, clearer skies and higher values indicate brighter or otherwise poorer viewing conditions.

We began by constructing four nightly "badness" components from the underlying environmental variables: anthropogenic skyglow from Black Marble radiance (NTL_{jt}), lunar irradiance (LUN_{jt}), aerosol optical thickness (AOT_{jt}), and relative humidity (RH_{jt}). Because these inputs differ in scale and some exhibit strong right-skew, each variable was first evaluated for non-normality. When the D'Agostino–Pearson normality test rejected normality at $p < 0.05$ and absolute skewness exceeded 1.0, we applied a log-plus-one transformation:

$$\tilde{x}_{jt} = \ln\left(1 + \max\{x_{jt}, 0\}\right). \tag{1}$$

Otherwise, the original scale was retained. Each transformed (or untransformed) series was then robustly rescaled to the unit interval using the 1st and 99th percentiles of the full sample distribution:

$$B_x(x_{jt}) = \min\left\{1, \max\left[0, \frac{x_{jt} - Q_{0.01}(x)}{Q_{0.99}(x) - Q_{0.01}(x)}\right]\right\}, \tag{2}$$

where $Q_{0.01}(x)$ and $Q_{0.99}(x)$ are the 1st and 99th percentiles of variable x. This produced four normalized component scores on $[0, 1]$:

$$\begin{aligned} S_{jt} &= B_{\text{NTL}}\left(\text{NTL}_{jt}\right), \\ M_{jt} &= B_{\text{LUN}}\left(\text{LUN}_{jt}\right), \\ A_{jt} &= B_{\text{AOT}}\left(\text{AOT}_{jt}\right), \\ H_{jt} &= B_{\text{RH}}\left(\text{RH}_{jt}\right), \end{aligned} \tag{3}$$

where higher values indicate worse conditions for dark sky viewing.

Cloudiness was treated separately using Black Marble cloud-confidence information. When the cloud-confidence layer was available, we defined a binary cloudy-night indicator equal to one for confidence classes 2 or 3, and mapped cloud confidence into a partial cloud penalty:

$$C_{jt} \in \{0.00, 0.33, 0.67, 1.00\}, \tag{4}$$

corresponding to cloud-confidence classes 0, 1, 2, and 3, respectively. When only a clear-sky indicator was available, we set $C_{jt} = 1 - \text{Clear}_{jt}$. This treatment preserves gradation for partially compromised nights while still allowing fully cloudy nights to be handled as effectively unusable for stargazing.

The central innovation of the index is that atmospheric conditions do not enter only as additive penalties. Instead, aerosols and humidity are modeled as *amplifiers* of the visual effect of existing skyglow. This reflects the physics of nocturnal visibility more faithfully than a purely additive index: haze and moisture not only make the sky brighter in their own right, but also increase the scattering and apparent intensity of anthropogenic light already present in the atmosphere. We therefore define an atmospheric amplification factor as

$$\Phi_{jt} = 1 + 0.5A_{jt} + 0.5H_{jt}, \tag{5}$$

and then compute *effective skyglow* as

$$S^*_{jt} = \min\{1,\ S_{jt}\Phi_{jt}\}. \tag{6}$$

Equations 5 and 6 imply that aerosols and humidity worsen experienced night sky quality most strongly when anthropogenic skyglow is already present. In other words, poor atmospheric conditions multiply the welfare-relevant effect of existing artificial light rather than simply adding a constant increment to brightness.

We then combined effective skyglow and moonlight into a nightly darkness "badness" score:

$$D_{jt} = 0.6S^*_{jt} + 0.4M_{jt}, \tag{7}$$

which was calculated only for park-nights with non-missing skyglow and moonlight information. A partial cloud penalty was then added:

$$D_{jt}^{\text{obs}} = \min\{1,\ D_{jt} + 0.25C_{jt}\}\,. \tag{8}$$

The Bortle Dark Sky Index was obtained by mapping this badness score linearly to the conventional 1–9 Bortle range:

$$\text{OBDI}_{jt} = 1 + 8D_{jt}^{\text{obs}}, \tag{9}$$

with the corresponding discrete class defined as

$$\text{Class}_{jt} = \text{round}\,(\text{OBDI}_{jt})\,, \qquad \text{Class}_{jt} \in \{1, \ldots, 9\}. \tag{10}$$

When a night was classified as cloudy, we forced the continuous and discrete values to 9, indicating that star visibility was effectively too poor for meaningful dark sky recreation regardless of the underlying moonlight or anthropogenic lighting conditions.

Although the index is nonlinear by construction, we also estimated a standardized linear approximation as a descriptive diagnostic of component importance by regressing OBDI_{jt} on z-standardized versions of the four underlying components and converting the absolute coefficient magnitudes into relative weights. We emphasize, however, that these diagnostic weights are not the construction rule for the index itself. The substantive contribution of the index is its interactive formulation: aerosols and humidity act through amplification of skyglow, clouds impose a separate usability penalty, and moonlight enters as a parallel source of nocturnal brightening. This structure allows the index to better reflect the experienced quality of the night sky than a purely additive linear composite and aligns the measure used in the econometric analysis with the underlying physics of atmospheric scattering and visibility.

4.4 Validation of the Bortle Dark Sky Index

We validated the Bortle Dark Sky Index against independent ground truth night sky observations using matched Sky Quality Meter (SQM) readings obtained through Globe at Night [4]. The validation sample consisted of park-specific nightly observations for which both the constructed index and a corresponding SQM measure were available. Because SQM readings are reported in magnitudes per square arcsecond, higher SQM values indicate darker skies, whereas higher values of the Bortle Dark Sky Index indicate brighter and poorer viewing conditions. We therefore expected a negative association between the two measures.

The index was negatively and significantly correlated with the ground truth SQM data ($n = 24$, $r = -0.512$, $p = 0.011$) (Supplementary Information, Figure S1, Panel B). The fitted relationship indicates that nights assigned lower Bortle Dark Sky Index values tended to correspond to higher SQM readings, consistent with darker observed sky conditions, whereas higher Bortle Dark Sky Index values were associated with lower SQM readings and therefore brighter observed skies. Although the relationship is not perfect, the direction and statistical significance of the association provide evidence of convergent validity between the remotely constructed index and independent field-based measures of sky brightness. Taken together, these results indicate that the Bortle Dark Sky Index captures meaningful variation in experienced night sky quality and is suitable for use as the night sky state variable in the econometric analysis.

4.5 Site Choice Model

We first computed travel cost using distance and duration outputs from the Google Maps API service (Distance Matrix), combined with vehicle operating costs and opportunity cost of travel time such that:

$$C_{nj} = 2\left(\frac{\rho \times \text{dist}_{nj}}{\text{group size}} + \theta \times \text{wage}_n \times \text{time}_{nj}\right), \tag{11}$$

where dist_{nj} is one-way distance (miles), time_{nj} is one-way travel time (hours), ρ is a per-mile operating cost proxied by the IRS standard mileage rate (e.g., 58.5¢/mile for early 2022), group size is the number of people traveling (including the respondent), and θ is the value-of-time fraction (set to 0.33 of the implied hourly wage based on reported household income midpoint divided by 2,080 hours).

For visitors who stopped at multiple parks (as indicated by a 'check all that apply' question on the survey), we: (i) calculated the total travel distance and time from the respondent's home zip code to all their selected destinations together (i.e., a multi-destination trip) and each destination in isolation (i.e., a single-destination trip); (ii) summed the set of single-destination trips' distances and times; and then (iii) apportioned the multi-destination trip distance and time according to the fraction represented by the surveyed park relative to the summed single-destination distances and times. This is conceptually similar to Parsons et al.'s [57] approach.

We then estimated multi-site random utility (site choice) models in which each respondent n chose one park unit j from a fixed alternative set J on the observed trip date t. Utility was specified as

$$U_{njt} = V_{njt} + \varepsilon_{njt}, \tag{12}$$

with representative utility

$$V_{njt} = \delta_j + \beta_c \widetilde{\ln(C_{nj})} + \beta X_{jt}, \tag{13}$$

where δ_j are park fixed effects (alternative-specific constants), $\widetilde{\ln(C_{nj})}$ is the z-standardized logarithm of respondent-specific travel cost to site j, and $\mathbf{X}_{jt}$ contains the site- and date-specific attributes included in a given specification. Assuming i.i.d. extreme value errors yields the standard conditional logit probability:

$$P_{njt} = \frac{\exp\left(V_{njt}\right)}{\sum_{k \in J} \exp\left(V_{nkt}\right)}. \tag{14}$$

The estimation data were organized as a respondent-by-alternative panel in which each surveyed trip was paired with site- and night-specific environmental conditions for all parks in the 36-site choice set. Travel cost entered in logarithmic form, and the final estimation sample was restricted to respondents who reported participation in at least one dark sky dependent activity (night sky viewing, night sky photography, or nighttime wildlife observation). Site-night conditions were assembled by merging the processed survey choice panel with nightly park-level meteorological data and the two night sky representations used in the analysis: (i) the calibrated mean all-sky Anthropogenic Light Ratio (ALR), and (ii) the Bortle Dark Sky Index together with its residualized component diagnostics. Dates were normalized before merging so that reported trip dates aligned exactly with the environmental panel, and estimation was restricted to valid choice sets in which exactly one alternative was observed as chosen.

Model construction proceeded sequentially to establish the baseline travel cost form and select the meteorological controls (Supplementary Information, Table S2). The final estimation stage then focused on two conceptually distinct representations of night sky conditions. The first used the calibrated mean all-sky ALR as an alternative measure focused specifically on anthropogenic skyglow. The second specification replaced the ALR measure with the Bortle Dark Sky Index as the primary state variable, augmented with residualized versions of selected underlying components—skyglow, moonlight, and humidity—to assess whether those dimensions retained explanatory content beyond the composite index itself. These residual terms capture variation in the components not already summarized by the Bortle Dark Sky Index. Because the ALR measure and the Bortle Dark Sky Index capture overlapping aspects of nocturnal conditions, they were evaluated in separate specifications rather than entered simultaneously.

To stabilize estimation and place continuous predictors on a common scale, the final models used z-standardized versions of log travel cost, minimum temperature, precipitation, wind speed, the calibrated mean all-sky ALR, the Bortle Dark Sky Index, and the residualized Bortle components. Park fixed effects were included through a full set of park-unit indicators with one omitted reference category. Competing specifications were compared using Akaike's Information Criterion (AIC), computed as $-2\ell + 2K$, where ℓ is the model log-likelihood and K is the number of estimated parameters.

4.6 Marginal Willingness to Pay

Marginal willingness to pay (MWTP) for an attribute $x \in \mathbf{X}_{jt}$ is recovered from the ratio of the attribute coefficient to the (negative) marginal utility of travel cost. With log travel cost in utility, the implied MWTP for a one-unit change in attribute x is local and depends on the cost level at which it is evaluated:

$$MWTP_x(C) = -\frac{\beta_x}{\beta_c}\, C. \tag{15}$$

For reporting, we evaluate MWTP at a sample-relevant cost level (e.g., mean C_{nj}) to express dollars per unit change in each attribute for the sampled choice context. In the case of the Bortle Dark Sky Index, this yields the implied willingness to pay for a one-unit improvement in effective night sky quality, holding site constants and other observed conditions fixed. Because the MWTP estimates are derived from behavioral data and site-night conditions observed during April, May, September, and October, they should be interpreted as season-specific marginal welfare measures for visitors observed during this sampling window, rather than as year-round values. Welfare calculations from logit-based site choice models follow standard random-utility results (e.g., log-sum surplus) and provide the basis for subsequent accounting and scenario analysis.

4.7 Aggregate Welfare At Risk

We estimate welfare at risk from deteriorating night sky conditions by simulating a park-specific degradation shock equal to 0.1 standard deviations of the relevant night sky metric and translating the induced utility change into compensating variation. Let Q_{jm} denote the observed night sky quality measure for park j in month m, where Q_{jm} is represented either by the monthly mean Bortle Dark Sky Index or by the monthly mean calibrated all-sky ALR. For each park j, let $\sigma_j(Q)$ denote the standard deviation of the relevant metric over the observed panel. We define the counterfactual as

$$Q_{jm}^{\mathrm{CF}} = Q_{jm} + 0.1\,\sigma_j(Q), \tag{16}$$

so that

$$\Delta Q_{jm} = Q_{jm}^{\mathrm{CF}} - Q_{jm} = 0.1\,\sigma_j(Q). \tag{17}$$

For each park-month, the per-person welfare loss is then computed from the ratio of the night sky coefficient to the travel-cost coefficient, evaluated at the sample mean travel cost:

$$\Delta W_{jm}(\bar{C}) = \left| \bar{C} \left[\exp\left(-\frac{\beta_q}{\beta_c}\,\Delta Q_{jm} \right) - 1 \right] \right|, \tag{18}$$

where $\bar{C}$ is the mean travel cost in the estimation sample, β_q is the estimated coefficient on the relevant night sky metric, and β_c is the coefficient on log travel cost. Because the expression is reported as welfare loss, we use the absolute value of the compensating variation term.

Aggregate losses were then constructed by combining these park-month per-person losses with administrative visitation data from the U.S. National Park Service and the Utah Division of State Parks. Monthly visitation counts were first adjusted to approximate unique visitors using alternative re-entry assumptions of 3.2 visits per visitor (lower-bound losses) and 1.1 visits per visitor (upper-bound losses), consistent with the idea that administrative counts reflect visits rather than unique individuals [58, 59]. The resulting unique-visitor counts were then multiplied by the survey-based estimate that 50% of visitors engaged in dark sky dependent recreation, yielding the number of affected visitors in each park-month. Aggregate welfare loss for each park-month was obtained by multiplying the per-person loss in Eq. 18 by these adjusted visitor totals, and total losses were then summed across the four sampled months (April, May, September, and October) of 2021.

This aggregation procedure is intentionally aligned to the monthly environmental and visitation data used in the scenario calculations rather than to a daily trip-probability accounting framework. It therefore produces a seasonally consistent estimate of welfare at risk over the sampled shoulder-season months under park-specific degradation shocks equal to 0.1 standard deviations of the relevant night sky metric, while preserving the uncertainty range implied by alternative assumptions about visitor re-entry.

Resource Availability

All data and code are publicly available at https://github.com/JordanSmithPhD/alan-ces.

Acknowledgements

This research was funded jointly by the Natural Sounds and Night Sky Division of the U.S. National Park Service (Task Agreement P20AC00525) and by the Public Lands Initiative at Utah State University (UTAO + Number 1566).

Author Contributions

JWS and AJB conceived and designed the study. JWS, AJB, ZDM, SA, and AM led the development of the on-site visitor survey instrument. JWS, EJW, and CCL led the implementation of the on-site survey. AJB facilitated coordination with the study's national park units. JWS, SA, and PT developed the construction of the Bortle Dark Sky Index. JWS and PT constructed the site-choice models. JWS led all data preparation and analyses, visualizations, and developed the first draft of the manuscript. All authors contributed to subsequent revisions and approved the final version.

Declarations of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Hölker, F. *et al.* The dark side of light: A transdisciplinary research agenda for light pollution policy. *Ecology and Society* **15** (2010).

[2] Falchi, F. *et al.* The new world atlas of artificial night sky brightness. *Science Advances* **2**, e1600377 (2016).

[3] Kyba, C. C. M. *et al.* Artificially lit surface of Earth at night increasing in radiance and extent. *Science Advances* **3**, e1701528 (2017).

[4] Kyba, C. C. M., Altıntaş, Y. Ö., Walker, C. E. & Newhouse, M. Citizen scientists report global rapid reductions in the visibility of stars from 2011 to 2022. *Science* **379**, 265–268 (2023).

[5] Gaston, K. J., Visser, M. E. & Hölker, F. The biological impacts of artificial light at night: The research challenge. *Philosophical Transactions of the Royal Society B: Biological Sciences* **370**, 20140133 (2015).

[6] Gaston, K. J., Bennie, J., Davies, T. W. & Hopkins, J. The ecological impacts of nighttime light pollution: A mechanistic appraisal. *Biological Reviews* **88**, 912–927 (2013).

[7] Gaston, K. J., Duffy, J. P., Gaston, S., Bennie, J. & Davies, T. W. Human alteration of natural light cycles: Causes and ecological consequences. *Oecologia* **176**, 917–931 (2014).

[8] Jägerbrand, A. K. & Spoelstra, K. Effects of anthropogenic light on species and ecosystems. *Science* **380**, 1125–1130 (2023).

[9] Dunn, N. & Edensor, T. (eds) *Dark Skies: Places, Practices, and Communities* (Routledge, London, 2023).

[10] Cho, Y. *et al.* Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment. *Chronobiology International* **32**, 1294–1310 (2015).

[11] Nadybal, S. M., Collins, T. W. & Grineski, S. E. Light pollution inequities in the continental United States: A distributive environmental justice analysis. *Environmental Research* **189**, 109959 (2020).

[12] Tsao, J. Y., Saunders, H. D., Creighton, J. R., Coltrin, M. E. & Simmons, J. A. Solid-state lighting: An energy-economics perspective. *Journal of Physics D: Applied Physics* **43**, 354001 (2010).

[13] Saunders, H. D. & Tsao, J. Y. Rebound effects for lighting. *Energy Policy* **49**, 477–478 (2012).

[14] Lyytimäki, J. Nature's nocturnal services: Light pollution as a non-recognised challenge for ecosystem services research and management. *Ecosystem Services* **3**, e44–e48 (2013).

[15] Zielinska-Dabkowska, K. M., Schernhammer, E. S., Hanifin, J. P. & Brainard, G. C. Reducing nighttime light exposure in the urban environment to benefit human health and society. *Science* **380**, 1130–1135 (2023).

[16] Díaz, S. *et al.* Assessing nature's contributions to people. *Science* **359**, 270–272 (2018).

[17] Daniel, T. C. *et al.* Contributions of cultural services to the ecosystem services agenda. *Proceedings of the National Academy of Sciences* **109**, 8812–8819 (2012).

[18] Chan, K. M. A., Satterfield, T. & Goldstein, J. Rethinking ecosystem services to better address and navigate cultural values. *Ecological Economics* **74**, 8–18 (2012).

[19] Potschin-Young, M. *et al.* Understanding the role of conceptual frameworks: Reading the ecosystem service cascade. *Ecosystem Services* **29**, 428–440 (2018).

[20] Haines-Young, R. & Potschin, M. in *The links between biodiversity, ecosystem services and human well-being* (eds Raffaelli, D. G. & Frid, C. L. J.) *Ecosystem Ecology: A New Synthesis* BES Ecological Reviews Series, 110–139 (Cambridge University Press, Cambridge, UK, 2010).

[21] Spangenberg, J. H., von Haaren, C. & Settele, J. The ecosystem service cascade: Further developing the metaphor. Integrating societal processes to accommodate social processes and planning, and the case of bioenergy. *Ecological Economics* **104**, 22–32 (2014).

[22] Bateman, I. J. *et al.* Bringing ecosystem services into economic decision-making: Land use in the United Kingdom. *Science* **341**, 45–50 (2013).

[23] European Southern Observatory. How light pollution affects the dark night skies (2022).

[24] Kocifaj, M., Solano-Lamphar, H. A. & Videen, G. Night-sky radiometry can revolutionize the characterization of light-pollution sources globally. *Proceedings of the National Academy of Sciences* **116**, 7712–7717 (2019).

[25] Langston, S. & Taylor, K. Evaluating the benefits of dark and quiet skies in an age of satellite mega-constellations. *Space Policy* **68**, 101611 (2024).

[26] Kocifaj, M., Kundracik, F., Barentine, J. C. & Bará, S. The proliferation of space objects is a rapidly increasing source of artificial night sky brightness. *Monthly Notices of the Royal Astronomical Society: Letters* **504**, L40–L44 (2021).

[27] Barentine, J. C. *et al.* Aggregate effects of proliferating low-Earth-orbit objects and implications for astronomical data lost in the noise. *Nature Astronomy* **7**, 252–258 (2023).

[28] Beeco, J. A. *et al.* Support for management actions to protect night sky quality: Insights from visitors to state and national park units in the U.S. *Journal of Environmental Management* **345**, 118878 (2023).

[29] Kocifaj, M., Wallner, S. & Barentine, J. C. Measuring and monitoring light pollution: Current approaches and challenges. *Science* **380**, 1121–1124 (2023).

[30] Kyba, C. C. M., Ruhtz, T., Fischer, J. & Hölker, F. Cloud coverage acts as an amplifier for ecological light pollution in urban ecosystems. *PLOS ONE* **6**, e17307 (2011).

[31] Levin, N. *et al.* Remote sensing of night lights: A review and an outlook for the future. *Remote Sensing of Environment* **237**, 111443 (2020).

[32] Russell, Z. *et al.* Communicating darkness: Visitor preferences for night sky interpretation. *Journal of Interpretation Research* (2026).

[33] Simpson, S. N. & Hanna, B. G. Willingness to pay for a clear night sky: Use of the contingent valuation method. *Applied Economics Letters* **17**, 1095–1103 (2010).

[34] Mitchell, D. & Gallaway, T. Dark sky tourism: Economic impacts on the Colorado Plateau Economy, USA. *Tourism Review* **74**, 930–942 (2019).

[35] Parsons, G. R., Plantinga, A. J. & Boyle, K. J. Narrow choice sets in a random utility model of recreation demand. *Land Economics* **76**, 86–99 (2000).

[36] Parsons, G. R. & Kealy, M. J. A demand theory for number of trips in a random utility model of recreation. *Journal of Environmental Economics and Management* **29**, 357–367 (1995).

[37] Daily, G. C. *et al.* Ecosystem services in decision making: Time to deliver. *Frontiers in Ecology and the Environment* **7**, 21–28 (2009).

[38] Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University. 2016. High Resolution Settlement Layer (HRSL) (2024).

[39] Bortle, J. E. Gauging light pollution: The Bortle dark-sky scale (2006).

[40] Bará, S., Falchi, F., Lima, R. C. & Pawley, M. Keeping light pollution at bay: A red-lines, target values, top-down approach. *Environmental Challenges* **5**, 100212 (2021).

[41] Longcore, T. & Rich, C. Ecological light pollution. *Frontiers in Ecology and the Environment* **2**, 191–198 (2004).

[42] Bará, S. & Lima, R. C. Photons without borders: Quantifying light pollution transfer between territories. *International Journal of Sustainable Lighting* **20**, 51–61 (2018).

[43] Hung, L.-W., Duriscoe, D. M., White, J. M., Meadows, B. & Anderson, S. J. Night skies data report: Photometric assessment of night sky quality–Chaco Culture National Historical Park. NPS/NRSS/NSNSD/NRR 2019/1914, U.S. Department of the Interior, National Park Service, Fort Collins, CO (2019).

[44] Duriscoe, D. M. Measuring anthropogenic sky glow using a natural sky brightness model. *Publications of the Astronomical Society of the Pacific* **125**, 1370 (2013).

[45] National Park Service. Night sky maps. https://www.nps.gov/subjects/nightskies/night-sky-maps.htm (2026).

[46] Smith, J. W. *et al.* Characteristics, management preferences, and spending profiles of night sky recreationists in Utah. Tech. Rep., Institute of Outdoor Recreation and Tourism, Logan, UT (2023).

[47] Lamprecht, C. Meteostat Python (2026).

[48] Junninen, H., Niska, H., Tuppurainen, K., Ruuskanen, J. & Kolehmainen, M. Methods for imputation of missing values in air quality data sets. *Atmospheric Environment* **38**, 2895–2907 (2004).

[49] Duriscoe, D. M., Anderson, S. J., Luginbuhl, C. B. & Baugh, K. E. A simplified model of all-sky artificial sky glow derived from VIIRS Day/Night band data. *Journal of Quantitative Spectroscopy and Radiative Transfer* **214**, 133–145 (2018).

[50] NASA VIIRS Land Science Investigator-Led Processing System. VIIRS/NPP gap-filled lunar BRDF-adjusted nighttime lights daily L3 global 500m linear lat lon grid (2025).

[51] Román, M. O. *et al.* NASA's Black Marble nighttime lights product suite. *Remote Sensing of Environment* **210**, 113–143 (2018).

[52] Gelaro, R. *et al.* The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) (2017).

[53] Global Modeling and Assimilation Office. MERRA-2 inst3_2d_gas_Nx: 2d, 3-Hourly, Instantaneous, Single-Level, Assimilation, Aerosol Optical Depth Analysis V5.12.4 (2015).

[54] Randles, C. A. *et al.* The MERRA-2 aerosol reanalysis, 1980 onward. Part I: System description and data assimilation evaluation (2017).

[55] Copernicus Climate Change Service. ERA5 hourly data on single levels from 1940 to present (2026).

[56] Hersbach, H. *et al.* The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* **146**, 1999–2049 (2020).

[57] Parsons, G. *et al.* A site-portfolio model for multiple-destination recreation trips: Valuing trips to National Parks in the Southwestern United States. *Journal of the Association of Environmental and Resource Economists* **8**, 1–25 (2021).

[58] Cook, P. S. Impacts of visitor spending on the local economy. NPS/NRSS/EQD/NRR 2014/806, U.S. Department of the Interior, National Park Service, Natural Resource Stewardship and Science, Fort Collins, CO (2014).

[59] Stynes, D. J. Impact of visitor spending on the local economy: Zion National Park, 2006. Tech. Rep., Michigan State University, East Lansing, MI (2008).

Supplementary Information

Table S1 Characteristics of visitors participating in a dark sky dependent activity across nine park units in the Colorado Plateau ($n = 383$).

Characteristic	n	Mean	Std. Dev.	%
Sociodemographic Characteristics				
Gender				
Male	199			52.2
Female	178			46.7
Other	4			1.0
Age	371	47.5	16.7	
Education				
High school graduate or less	15			3.9
Vocational certificate	10			2.6
Some college or associate's degree	49			12.7
Bachelor's degree	165			42.9
Master's degree	100			26.0
Professional or doctoral degree	46			11.9
Annual Household Income				
Less than $25,000	19			5.3
$25,000 to $34,999	21			5.8
$35,000 to $49,999	26			7.2
$50,000 to $74,999	52			14.4
$75,000 to $99,999	59			16.4
$100,000 to $149,999	85			23.6
$150,000 to $199,000	40			11.1
$200,000 or more	58			16.1
Perceptual Characteristics				
Aware of Dark Sky Park Designation				
Yes	172			46.6
No	197			53.4
Behavioral Characteristics				
Travel distance (km)	359	887.56	951.44	
Travel duration (hours)	359	8.42	8.71	
Per-person travel cost (2021 USD)	333	$614.03	$737.73	

Table S2 Results of the conditional logit site choice models fit to dark sky dependent visitors.

Base Model			
Independent Variable	**Coef.**	**Std. Err.**	$P > \|z\|$
Travel Cost (log)	-2.532	0.218	< 0.001
Meteorological Model			
Independent Variable	**Coef.**	**Std. Err.**	$P > \|z\|$
Travel Cost (log)	-2.595	0.221	< 0.001
Minimum Temperature	0.962	0.230	< 0.001
Precipitation	-1.376	0.268	< 0.001
Windspeed	-0.510	0.167	0.002
Meteorological + Anthropogenic Light Ratio Model			
Independent Variable	**Coef.**	**Std. Err.**	$P > \|z\|$
Travel Cost (log)	-2.726	0.231	< 0.001
Minimum Temperature	0.849	0.233	< 0.001
Precipitation	-1.181	0.248	< 0.001
Windspeed	-0.513	0.170	0.003
Anthropogenic Light Ratio *(Calibrated Mean All-Sky)*	-3.273	1.192	0.006
Meteorological + Bortle Dark Sky Index Model			
Independent Variable	**Coef.**	**Std. Err.**	$P > \|z\|$
Travel Cost (log)	-2.633	0.225	< 0.001
Minimum Temperature	0.967	0.231	< 0.001
Precipitation	-1.253	0.260	< 0.001
Windspeed	-0.524	0.175	0.003
Bortle Dark Sky Index	-0.343	0.101	0.001
Meteorological + Bortle Dark Sky Index Model *(with Residuals)*			
Independent Variable	**Coef.**	**Std. Err.**	$P > \|z\|$
Travel Cost (log)	-2.692	0.227	< 0.001
Minimum Temperature	1.029	0.231	< 0.001
Precipitation	-1.091	0.243	< 0.001
Windspeed	-0.670	0.180	< 0.001
Bortle Dark Sky Index	-0.567	0.113	< 0.001
Skyglow Residual	-0.092	0.154	0.553
Lunar Irradiance Residual	-1.475	0.411	< 0.001
Humidity Residual	-1.052	0.244	< 0.001

Notes. $n = 333$. Coefficients for all alternative-specific constants are not shown for brevity. Log-likelihood values for each model are: Base Model = -569.34; Meteorological Model = -545.36; Meteorological + Anthropogenic Light Ratio Model = -538.10; Meteorological + Bortle Dark Sky Index Model = -538.56; Meteorological + Bortle Dark Sky Index Model *(with Residuals)* = -526.35.

Table S3 Results of the conditional logit site choice model fit to non-dark sky dependent visitors.

Meteorological + Anthropogenic Light Ratio Model			
Independent Variable	**Coef.**	**Std. Err.**	$P > \|z\|$
Travel Cost (log)	-4.272	0.459	< 0.001
Minimum Temperature	0.281	0.305	0.357
Precipitation	-0.941	0.317	0.003
Windspeed	-0.174	0.221	0.430
Anthropogenic Light Ratio	-6.641	2.285	0.004
Meteorological + Bortle Dark Sky Index Model *(with Residuals)*			
Independent Variable	**Coef.**	**Std. Err.**	$P > \|z\|$
Travel Cost (log)	-3.410	0.380	< 0.001
Minimum Temperature	0.509	0.292	0.081
Precipitation	-0.848	0.323	0.009
Windspeed	-0.334	0.223	0.133
Bortle Dark Sky Index	-0.368	0.144	0.011
Skyglow Residual	-0.105	0.208	0.613
Lunar Irradiance Residual	-0.150	0.627	0.811
Humidity Residual	-0.715	0.293	0.015

Notes. $n = 202$. Log-likelihood values for each model are: Meteorological + Anthropogenic Light Ratio Model = −286.72; Meteorological + Bortle Dark Sky Index Model *(with Residuals)* = −295.74.

Table S4 Consumer surplus comparison between dark sky dependent ($n = 333$) and non-dark sky dependent visitors ($n = 202$).

Meteorological + Anthropogenic Light Ratio Model		
Visitor Type	**Consumer Surplus Per Person Per Trip**	**Std. Err.**
Dark sky dependent	$225.57	$19.16
Non-dark sky dependent	$156.24	$16.77
Meteorological + Bortle Dark Sky Index Model *(with Residuals)*		
Visitor Type	**Consumer Surplus Per Person Per Trip**	**Std. Err.**
Dark sky dependent	$228.41	$19.30
Non-dark sky dependent	$195.76	$21.80

Notes. Mean per-person travel costs were: Dark sky dependent recreationists = $614.03, Non dark sky dependent recreationists = $665.89. Z-test across groups: Meteorological + Anthropogenic Light Ratio Model = $z = 2.72$, $p = 0.007$, Meteorological + Bortle Dark Sky Index Model *(with Residuals)* = $z = 1.12$, $p = 0.262$.

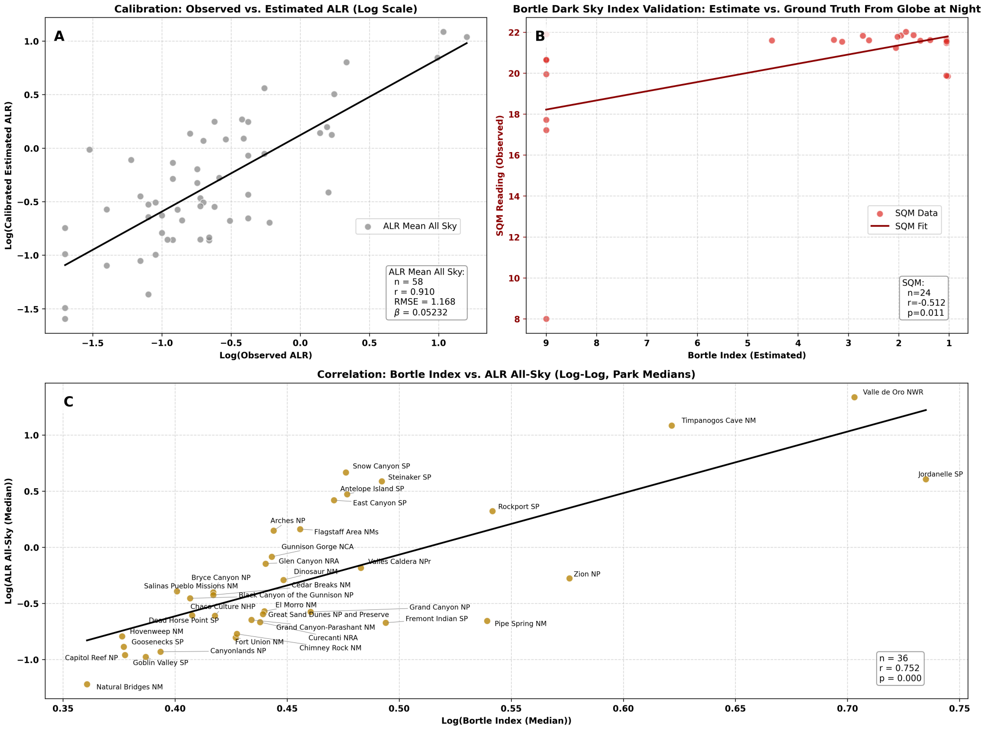

Fig. S1 Calibration of the Anthropogenic Light Ratio (ALR), validation of the Bortle Dark Sky Index, and robustness of the association between the two night sky state measures. (A) Log–log calibration of the calibrated mean all-sky ALR against ground-based National Park Service observations. Gray points show matched park-night observations, and the solid black line shows the fitted origin-constrained calibration relationship. The strong positive correspondence (n = 58, r = 0.910, $RMSE$ = 1.168, β = 0.05232) indicates that the VIIRS-based weighted radiance sums recover observed anthropogenic skyglow well across the sampled conditions. **(B)** Validation of the Bortle Dark Sky Index against independent ground-truth Sky Quality Meter (SQM) observations from Globe at Night [4]. Red points show matched park-night observations, and the dark red line shows the fitted linear trend. Because higher SQM values indicate darker skies, whereas higher Bortle Dark Sky Index values indicate brighter and poorer viewing conditions, the expected relationship is negative. Consistent with this expectation, the index is moderately and significantly associated with SQM readings (n = 24, r = -0.512, p = 0.011), supporting the convergent validity of the index as a remotely constructed measure of experienced night sky quality. **(C)** Robustness test of the association between the two night sky state measures using park-level medians of the log-transformed Bortle Dark Sky Index and log-transformed calibrated mean all-sky ALR. Each point represents one park unit, and the solid black line shows the fitted linear trend. The strong positive correlation (n = 36, r = 0.752, $p < 0.001$) indicates that parks with brighter median Bortle conditions also tend to exhibit higher median anthropogenic skyglow as measured by ALR, while still allowing meaningful differences between the broader realized-experience metric and the anthropogenic-only skyglow metric.

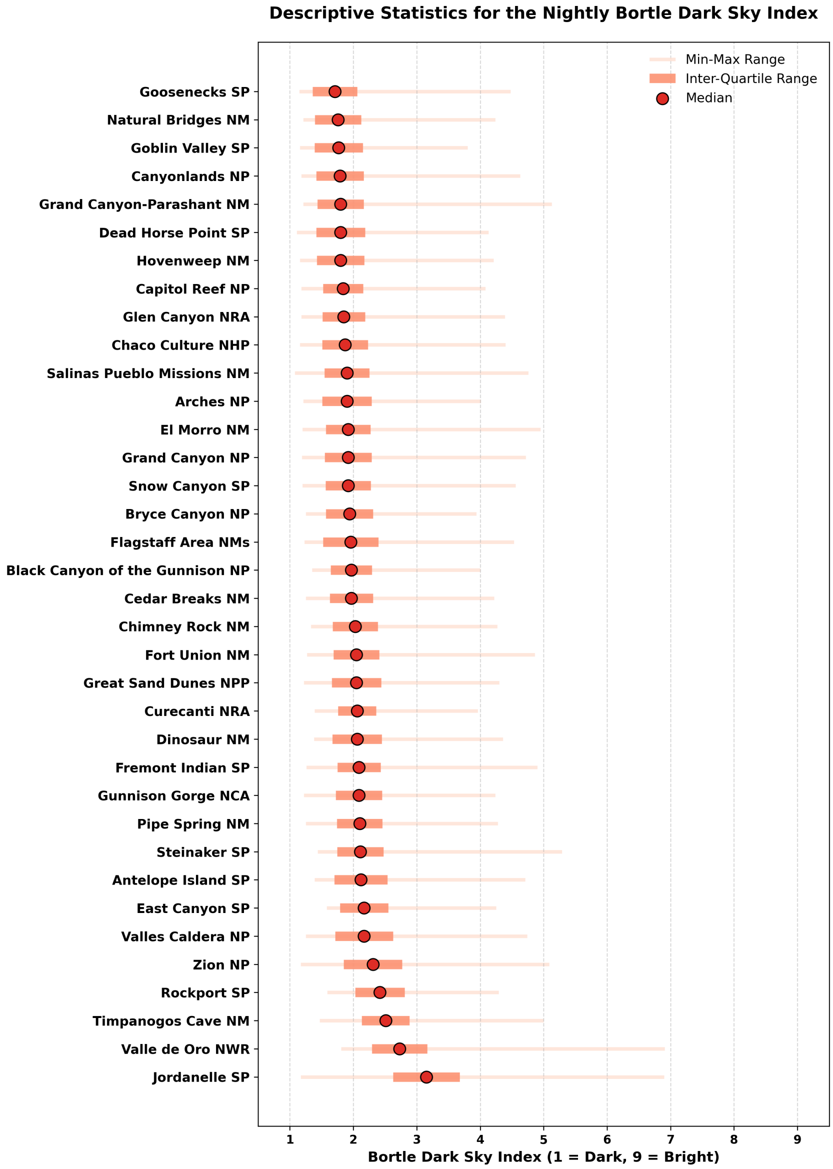

Fig. S2 Descriptive distribution of the nightly Bortle Dark Sky Index across study sites. Sites are ordered from darker median conditions at the top to brighter median conditions at the bottom. For each site, the light horizontal bar shows the full observed minimum-to-maximum range, the darker bar shows the interquartile range (25th to 75th percentile), and the red point marks the median. Lower index values indicate darker skies and higher night sky quality, whereas higher values indicate brighter skies. Most parks and monuments cluster around relatively dark conditions, with medians near Bortle values of roughly 1.5 to 2.5, while a smaller number of sites exhibit brighter median conditions and wider nightly variability. The plot highlights both central tendency and dispersion in observed nocturnal conditions, providing a descriptive baseline for subsequent site-choice and welfare analysis.