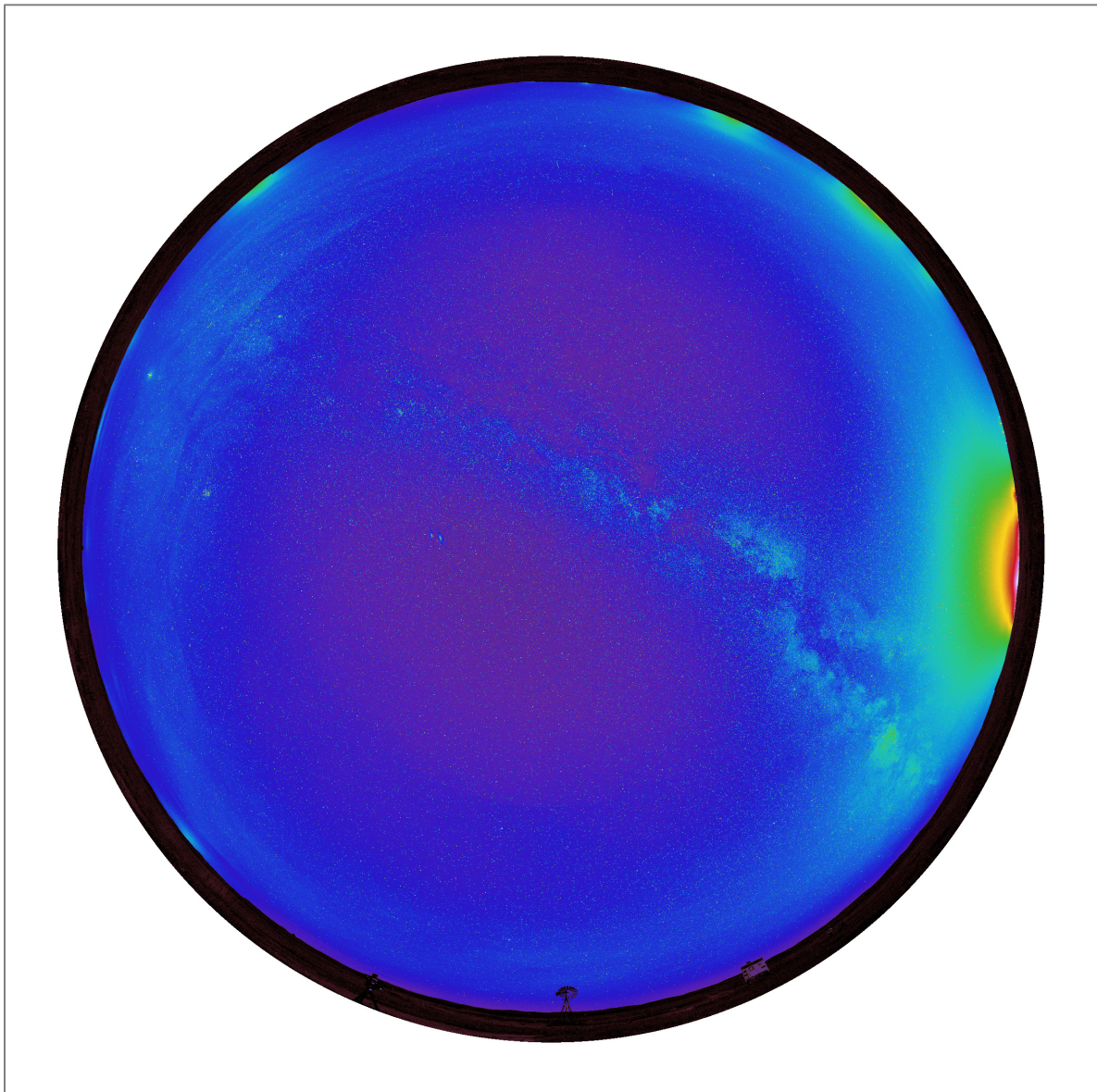




Night Skies Data Report

Photometric Assessment of Night Sky Quality at Niobrara National Scenic River



Fisheye view of the night sky over Niobrara National Scenic River in false color.
NPS/NIGHT SKIES PROGRAM

Night skies data report: Photometric assessment of night sky quality at Niobrara National Scenic River

Science Report NPS/SR—2025/288

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Abstract

This report characterizes night sky conditions in Niobrara National Scenic River (NIOB) using measurements made in the park unit and models of regional conditions based on satellite data. Calibrated night sky imagery was obtained to characterize the night sky at 2 sites. These ground-based observations were collected on 2 nights from 2024-08-29 to 2024-08-30. Satellite data from 2022 was used to create a map of predicted night sky conditions in and around the park.

The sky overhead remains pristine and unaffected by light pollution with an average zenith brightness of $21.62 \text{ mag/arcsec}^2$. We estimate more than 99% of stars were still visible for most of the night, providing a unique and unfettered opportunity to observe the natural night sky from the park. The whole sky over NIOB is 9%–18% (mean=14%) brighter than average natural levels, indicating excellent dark sky conditions on average.

In NIOB, we classified the sky as Bortle Class 2: typical truly dark site, based on the visibility of astronomical objects. The average naked eye limiting magnitude (NELM) is 6.75, which is approaching near pristine under average conditions. Our Sky Quality Meter (SQM-L) measurements average $21.44 \text{ mag/arcsec}^2$, slightly higher than average natural conditions, elevated by Milky Way and airglow luminance. Natural airglow is apparent along the horizon. M33, the Triangulum Galaxy, is seen rather easily with direct vision. The summer Milky Way is highly structured to the unaided eye and visible down to the horizon. Its brightest regions look like veined marble when viewed with ordinary binoculars. The main impact on NIOB's night sky quality is the light dome from Valentine, NE, with smaller impacts from Ainsworth, NE, Springview, NE, Sicangu Village, SD and Winner, SD. Of these Valentine is the largest and brightest. From Fort Niobrara, the Valentine light dome is the dominant feature of the landscape, significantly brighter than the Milky Way and any other natural feature, although limited to a small portion of the horizon. From Norden Bridge, the Valentine light dome is still the main source of anthropogenic light, and just slightly brighter than the Milky Way, although its footprint is much smaller at that distance and its impact on the overall scene is minimal.

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List of Terms or Acronyms

aerosol: Fine solid or liquid particles suspended in the air. Examples include dust, fume, mist, smoke and fog.

airglow: Naturally occurring light emitted from the gases in the upper atmosphere. It often appears as a vague and smooth light in the sky that is brighter toward the horizon as compared to the zenith. However, it can sometimes have a banded or wispy character and change in the timescale of minutes.

airmass: A measure of the amount of air through which light from outside the atmosphere must pass to reach the observer. It is expressed as a ratio of the atmospheric thickness along a line of sight to that at zenith. Mathematically, the airmass equals the secant of the zenith angle.

all-sky light pollution ratio (ALR): The ratio of anthropogenic to natural sky brightness averaged over the entire sky.

angle of incidence: The angle between a light ray's path striking a surface and a line perpendicular to the surface (sometimes called "normal" to a surface).

anthropogenic: Caused or generated by humans.

azimuth: Angle eastward of true north along the horizon. Moving clockwise on a 360° circle, north has azimuth 0°, east 90°, south 180°, and west 270°.

Bortle Class: A nine-level numeric scale that measures the night sky's brightness at a particular location based on visual observations (Bortle, 2001). It quantifies the observability of celestial objects and the interference caused by light pollution. The rating of one indicates pristine night sky and nine indicates heavily light-polluted sky.

charge-coupled device (CCD): A sensitive photon detector made out of a light-sensitive integrated circuit. Within the device, the electrical charge can be manipulated, for example conversion into a digital value.

crepuscular: Describing animals that are active primarily during dawn and dusk.

dark adaptation: The process by which the eye becomes adapted to dim environments.

extinction: The attenuation of light due to absorption and/or scattering.

extinction coefficient: A quantitative value for specifying the attenuation of light due to absorption and/or scattering. It is usually expressed in magnitude per airmass.

glare: Bright and uncomfortable light shining from the source directly to the observer.

haze: An atmospheric aerosol of sufficient concentration to be visible. The particles are so small that they cannot be seen individually but are still effective in visual range restriction.

horizontal illuminance: Illuminance falling upon a horizontally oriented surface, such as level ground.

illuminance: (1) The light falling upon a surface, or (2) a photometric measure of luminous light incident on a unit surface area. The derived SI unit of illuminance is the lux (lx).

km: Kilometer, a metric unit for measuring length. One kilometer is approximately 0.62 miles.

light dome: Skyglow from a distant source (such as an urban center) which takes the form of a dome due to the properties of atmospheric scattering of light.

light pollution: The alteration of natural light levels in the outdoor environment by manmade sources. Light pollution may degrade the utility, function, biota, or aesthetics of the surrounding environment. Light pollution includes glare, light trespass, and skyglow.

luminaire: The complete lighting unit, including the lamp, the fixture, and other parts.

luminance: The photometric measure of luminous intensity per unit area of a surface. It describes the amount of light that passes through or is emitted from a particular area and falls within a solid angle. Luminance is often measured in candela per square meter (cd/m^2) or lamberts (L).

magnitude (mag or mags): A measure of an astronomical source's brightness on an inverted logarithmic scale. Brighter sources have smaller magnitudes. A magnitude 0 star is one hundred times brighter than a magnitude 5 star.

Milky Way: A barred spiral galaxy containing our own Solar System. When observed from Earth, it appears as an irregular band of light encircling the celestial sphere. It is comprised of vast numbers of faint unresolved stars and dust. Its position and orientation in the sky vary with the seasons and throughout each night due to the orbit and spin of the Earth.

naked eye limiting magnitude (NELM): The apparent magnitude of the faintest object visible in the sky with the naked eye. The NELM will depend on the observer, and will increase with the eye's dark adaptation. On a clear night without the moon and light pollution, the limiting magnitude will be greater than magnitude 6.

nocturnal: Happening in or active during the night, or relating to the night.

photometry: The measurement of light describing the perceived brightness to the human eye or an astronomical object's brightness in various electromagnetic spectra.

seeing: A measure of the optical steadiness of the air, usually judged by looking at the scintillation of stars or by measuring the angular size of a point source in the image.

skyglow: Anthropogenic light scattered or reflected off of air molecules and atmospheric aerosols, leading to a brightening of the night sky. Skyglow is generally regarded as an aesthetic degradation of the night sky, and will illuminate an observer and the landscape unnaturally.

upward radiance: A term used to describe radiant energy emitted upward into the atmosphere. Upward radiance is often associated with remote sensing measures of light emission.

vertical illuminance: Illuminance striking an upright oriented surface, such as a wall or a piece of paper held up to the light.

zenith: The point on the celestial sphere directly overhead.

zodiacal light: A faint, smooth, and elongated swath of light visible in the night sky. The zodiacal light appears as a noticeable cone of light near the sun, most visible immediately after evening twilight in the west and immediately before morning twilight in the east. It is caused by sunlight scattered by the dust particles in orbit around the sun.

Introduction

The night sky is an inseparable element of wild areas for park visitors and wildlife. It reveals an astonishing view into the vast universe, provides markers of daily and seasonal cycles, and features reference points for navigation. Historically, celestial objects and astronomical phenomena have significantly influenced numerous cultures around the globe. Today, star parties often attract many visitors, bringing important benefits to local, regional and national economies. In the National Park Service (NPS), night sky programs are among the most popular interpretive activities at parks, providing unique educational opportunities and an immersive experience connecting visitors to nature. The night sky is a natural, cultural, educational, and economic resource.

The *Organic Act of 1916* specifies that the NPS shall conserve resources unimpaired for the enjoyment of future generations. The *General Authorities Act of 1970* specifies high standards for NPS management, referring to “superlative natural, historic, and recreation areas” with “superb environmental quality... managed for the benefit and inspiration of all the people of the United States.” Accordingly, section 4.10 of the *2006 NPS Management Policies* states: “The Service will preserve, to the greatest extent possible, the natural lightscapes of parks, which are natural resources and values that exist in the absence of human-caused light.”

The Natural Sounds and Night Skies Division, in collaboration with NPS regions, parks, and programs, provides service wide support for night sky and nocturnal resource conservation through measurements, modeling, critical analysis, knowledge synthesis, and informed decision making. This report measures night sky brightness using images taken from inside the park and from a satellite circling the globe. The images taken inside the park provide accurate measurements of the night sky that wildlife and park visitors experience. The satellite images measure the upward radiance of the nighttime earth, providing a regional perspective of the lights that are altering the night sky in the park. Collectively, these data specify the condition of the night sky and the locations of light sources that are degrading it.

In the Methods chapter, we describe data collection and processing procedures for night sky images taken in parks and satellite images of stray light from developed areas. In the Results chapter, we report the sky quality and identify influences from nearby cities as seen in the images. Next, we discuss the natural brightness variation, measurement uncertainty, data quality and anomalies, and glare in the Discussion chapter. Finally, the Conclusions chapter summarizes our findings. In Appendix A: Observation Notes and Panoramic Images, we provide the notes taken by the observers during data collection and a set of panoramic images for each observation event.

Regional Setting

Light from anthropogenic sources has altered the natural luminance of the night sky throughout the continental United States and across much of the globe (Falchi et al., 2016; Kyba et al., 2017). Light from anthropogenic sources that is scattered by or reflected off air molecules and atmospheric aerosols brightens the sky and washes out celestial objects. This anthropogenic scattered light is called skyglow. Light sources up to 300 km (~200 miles) distant can cause skyglow. Skyglow

artificially illuminates the landscape and degrades visitor opportunities to view planets, stars, galaxies, and other astronomical objects.

Niobrara National Scenic River (NIOB) lies within the Nebraska Sandhills and Dakota–Nebraska Eroded Tableland of north-central Nebraska, a region featuring mixed-grass prairies and some of the largest sand dunes in the Western Hemisphere. It protects a 120 km (76 mi)-long stretch of the Niobrara River in Brown, Cherry, Keya Paha, and Rock Counties. Niobrara National Scenic River begins at Borman Bridge near the city of Valentine and encompasses the Niobrara River Valley downstream to Mariaville, Nebraska (Figure 1). Six major ecosystem types converge in the valley including northern boreal forest, ponderosa pine forest, eastern deciduous forest, tallgrass prairie, mixed-grass prairie, and shortgrass prairie. This variety of ecosystems supports an exceptionally large variety of plants and animals, many of them at the limits of or beyond their usual range. The nearest populated centers in Nebraska are Valentine, Springview, Ainsworth, and Bassett. The nearest populated centers in South Dakota are Winner, Sicangu Village, and Mission.

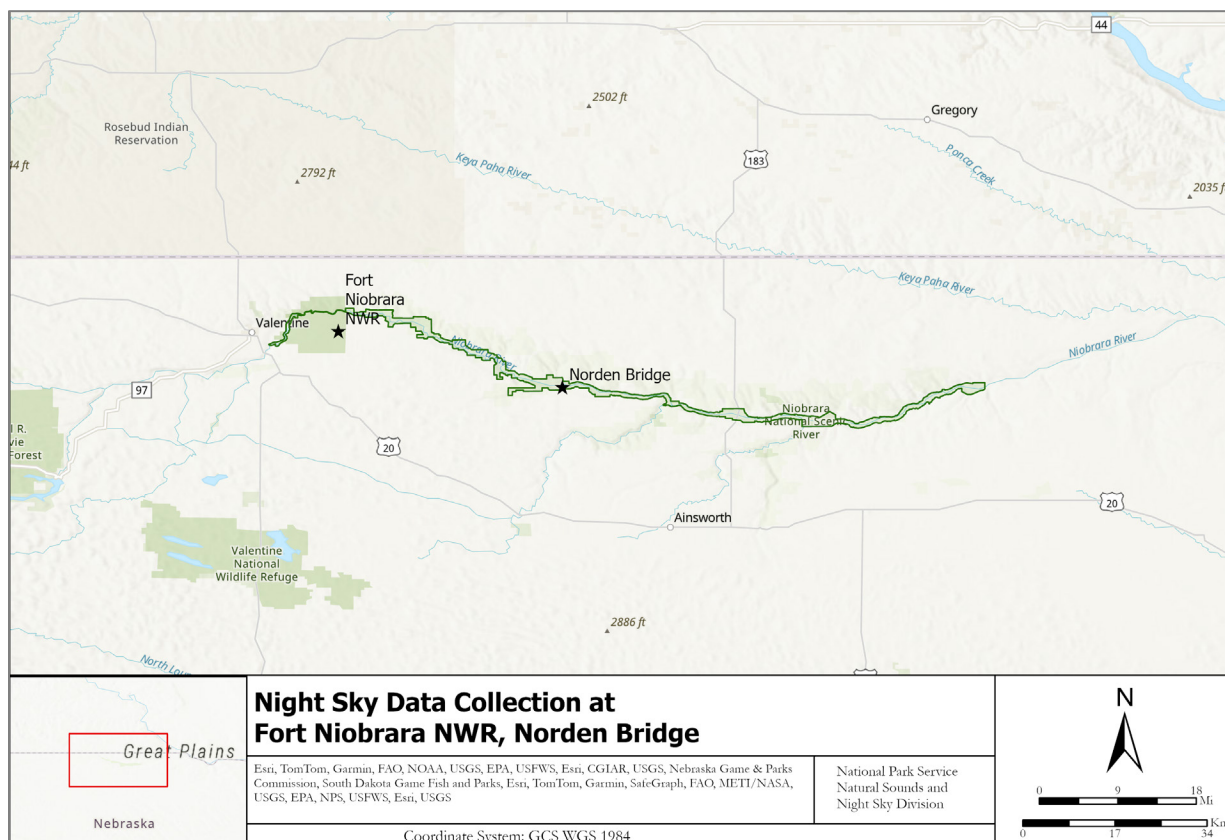


Figure 1. Geographic location of the park, including the 2 sites from the current study. Niobrara National Scenic River protects 120 km of the Niobrara River from Valentine, NE to Mariaville, NE. In general, light sources within 100 km could be visible and have the potential to brighten the night sky.

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Methods

Imaging the Night Sky

The NPS developed the camera system and the observing method to collect high-resolution images of the night sky from horizon to horizon (Duriscoe et al., 2007). The NPS camera system is composed of a commercial Nikon lens, a V-band filter, and a research-grade, monochromatic charge-coupled device (CCD). The filter only lets visible light pass through, allowing the detected signal to closely represent what human eyes can see based on our spectral sensitivity. Because each image has limited field of view, a set of images needs to be taken to cover the entire sky. A robotic mount is utilized to automatically position the camera for each image. Each image set takes up to 40 minutes to complete, depending on the specific system used and the exposure time. To minimize the amount of sun and moon light, data are collected when the sun is more than 18° below the horizon, and when the moon also is below the horizon. The weather conditions required for data collection are clear nights with almost no cloud cover.

Figure 2 shows a typical NPS Night Skies camera system used from 2010 onward. This camera system captures a composite image of the night sky by creating a mosaic from 45 images of portions of the sky, with each portion spanning a square 24° by 24° . Depending on the sky brightness at the observing site, the exposure time is usually set to be somewhere between 8 to 12 seconds for each image. Each resulting image set will yield a 40-million-pixel image mosaic covering the entire night sky and 7° below the horizon.



Figure 2. A typical National Park Service Night Skies Program camera system consists of a commercial lens, a V-band filter, and a CCD camera. The camera system is mounted on a motorized mount, hooked up to external batteries, and controlled by a computer.

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Between 8/29/2024 and 8/30/2024, NPS collected 2 nights of ground-based CCD camera data in NIOB, yielding 7 complete data sets. Each set is used to generate a panoramic image of the night sky. Table 1 lists the details about each data collection event, including the date, collection site, camera used, number of data sets collected, and observers.

Table 1. Ground-based data collection events at Niobrara National Scenic River. 'Sets' refers to the number of data sets taken that night; each set yields a panoramic image of the sky.

Date	Site Name	Camera	Sets	Observers
8/29/2024	Fort Niobrara NWR	ML 3	4	J White
8/30/2024	Norden Bridge	ML 3	3	J White

Locating Data Collection Sites

These observations with the CCD camera are carried out at specific sites in or near the park. In general, higher elevation sites free from nearby obstructions are selected because they provide a clear view of the sky down to the natural horizon. The sites also need to be free from bright and direct glare to prevent image saturation. Additional selection criteria include the accessibility and proximity of the site to stargazing locations, sensitive ecosystems, critical habitat, and future developments. For a small park, one clear site is sufficient to capture the conditions representable across the entire park. For a large park, strategic placement in relation to other measurement sites is also considered to capture the range of sky quality across the park. Each data collection site is listed in Table 2, and located on the map in Figure 1.

Table 2. Data collection sites at Niobrara National Scenic River.

Site Name	Elevation (m)	Latitude	Longitude
Fort Niobrara NWR	773	42.87526	-100.4071
Norden Bridge	681	42.78242	-100.0356

Fort Niobrara NWR

The Fort Niobrara NWR observation point is located in the Fort Niobrara National Wildlife Refuge approximately 2 miles south of Niobrara National Scenic River (NSR) and 7 miles east of Valentine, NE. From this observation point the light dome of Valentine, NE dominates the western horizon. Otherwise, the night sky is close to pristine. The Milky Way was visible from horizon to horizon, and faint airglow was visible.

Norden Bridge

The Norden Bridge observation point is located just south of Niobrara NSR near river mile 120 at the Niobrara Valley Preserve Trailhead visitor use area along Norden Ave. This location provides an expansive view of the surrounding environment, and due to its remote location is representative of the park's pristine night sky conditions.

Processing Night Sky Images

For each data set, we process the images to generate a panoramic view of the night sky with a resolution of 0.05 degrees per pixel (Duriscoe et al., 2007). The image processing procedures include basic noise (bias, dark, and flat-field) removal, linearity response correction, and absolute brightness calibration. We use the standard stars captured in the images as the position and brightness calibration sources. The images in a set are then mosaicked together, showing the panoramic view of the sky from the zenith to six degrees below the true horizon. Next, we build a model to separate out the natural light (Duriscoe, 2013). The observed panoramic images contain light from both natural and anthropogenic sources. We build a natural sky model to account for light from stars, planets, airglow, zodiacal light, and the Milky Way. We subtract out the modeled natural brightness to obtain panoramic images showing only the anthropogenic light. In summary, each data set yields a pair of

calibrated panoramic images, one showing the observed sky and the other showing the light only from anthropogenic sources.

Calculating Skyglow Impact from Nearby Cities

To expedite interpreting the all-sky images, we use Walker's Law to estimate predicted brightness of light domes. Brightness is expressed as a percent above natural sky luminance at a 45° angle above the horizon. The Dark Sky Association proposed using the Walker's Law in the following form:

$$I = 0.01 P d^{-2.5}$$

where

I = Walker's value indicating the skyglow level above the natural background

P = human population size taken from 2020 US Census Data

d = distance (km) to the population center.

At each observing location, we calculate the azimuth from the study site to the center based on the city centroid. The light dome brightness predicted by Walker's Law might not perfectly match what is captured in the images. Accurately predicting the light dome brightness is challenging.

Intrinsically, the characteristics of light domes depend on factors such as the illumination level per capita, the use of shielding, the distribution of lighting fixtures, and the spectral composition of light. Extrinsically, terrain shielding, atmospheric conditions, and variable natural light can also affect the appearance of light domes. There are more refined models (such as Duriscoe et al. 2018) for better predicting skyglow but here we choose to use Walker's Law for its simplicity.

Collecting Satellite Images of Earth at Night

Satellite based data were collected from the Suomi National Polar-orbiting Partnership (NPP, Lee et al. 2010), a weather satellite launched in 2011. This satellite mission is a collaborative effort between the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA). The on-board Visible Infrared Imaging Radiometer Suite (VIIRS) provides low-light measurements of upward radiance through the Day/Night Band (DNB) sensor (Lee et al., 2006). The spectral sensitivity of the VIIRS DNB ranges from 0.5 to 0.9 μm (Hillger et al., 2013), corresponding to light in green to near infrared. The DNB has a swath width of 3000 km and a pixel resolution of 742 m. The satellite has an orbital period of ~100 minutes, which allows for nightly global DNB imagery. The nightly observations are collected around 1:00 am local time.

Estimating Skyglow Using Satellite Data

Calibrated and processed images were obtained through the public archive on the Colorado School of Mines website (VIIRS - Payne Institute for Public Policy (mines.edu)). The VIIRS DNB sensor has on-orbit radiometric calibration and reports the radiance in units of $\text{W}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$ (Lee et al., 2014). These calibrated images are still subject to light from undesired sources and weather events. Baugh et

al. (2013) generated composite images by combining only high quality nighttime observations that were free of clouds, stray light, lunar illuminance, noisy edge of scan data, and missing data. We downloaded the annual composites generated from images taken in 2023 for the following analysis.

We use satellite imagery to estimate sky quality through a simple predictive model (Duriscoe et al., 2018). The 2023 annual composite from VIIRS DNB serves as a map of upward nighttime lights for our model input. The Simplified All-sky Light Pollution Ratio (SALR) uses geographic analysis tools to predict the average artificial luminance over the entire night sky. Specifically, this model is based upon a relation between skyglow brightness and the distance from the observer to the source of upward radiance. To display the result, we use ArcGIS to generate the thematic map of a region showing the modeled artificial sky brightness. This map is presented in the Results chapter.

Results

The ground-based observations yield the calibrated panoramic images of the night sky. Figure 3 shows an example of the image product associated with each data set. In Appendix A: Observation Notes and Panoramic Images, we provide links to the reference images for each night, both observed and artificial skyglow. We use magnitude per square arcsecond ($\text{mag}/\text{arcsec}^2$) for measuring the sky surface brightness. Magnitude (mag or mags) is a standard unit for measuring the brightness of astronomical objects and follows an inverted logarithmic scale. Under clear moonless conditions, a sky surface brightness of $22 \text{ mag}/\text{arcsec}^2$ would be considered pristine, and a sky surface brightness of $< 20 \text{ mag}/\text{arcsec}^2$ would be considered greatly deviated from the natural condition. The warmer colors in these images represent brighter skies. Figure 3 shows the observed night sky, which contains light from both natural and artificial sources. Purple and dark blue colors indicate an unpolluted sky, and the Milky Way under the natural condition appears green in this color scheme. Figure 4 shows only the light from artificial sources. Light domes along the horizon from the nearby area are more apparent in this bottom image.

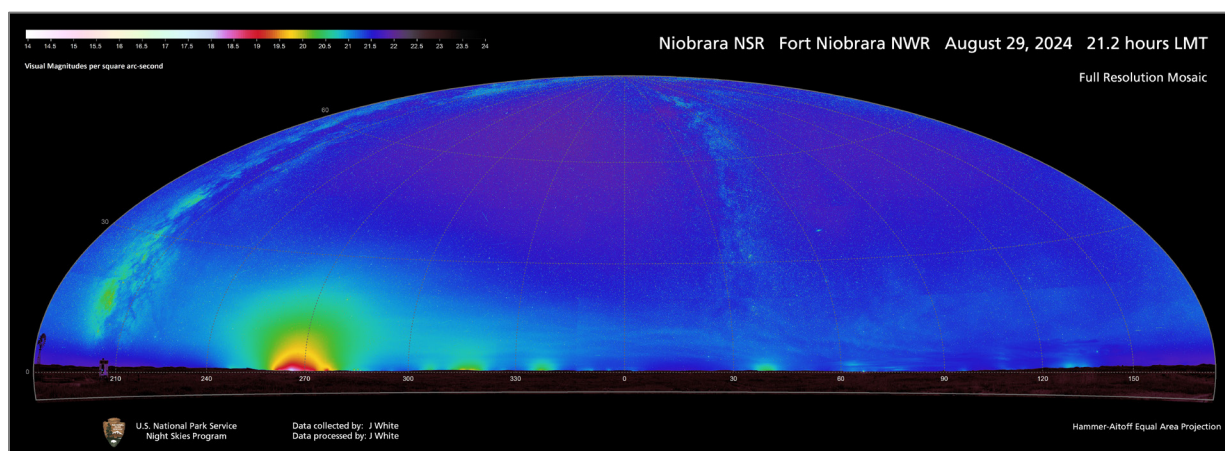


Figure 3. Panoramic image of the night sky from the Fort Niobrara NWR site on August 29, 2024. The grid lines are spaced 30° apart. The observed sky shows light from all sources, both natural and artificial.
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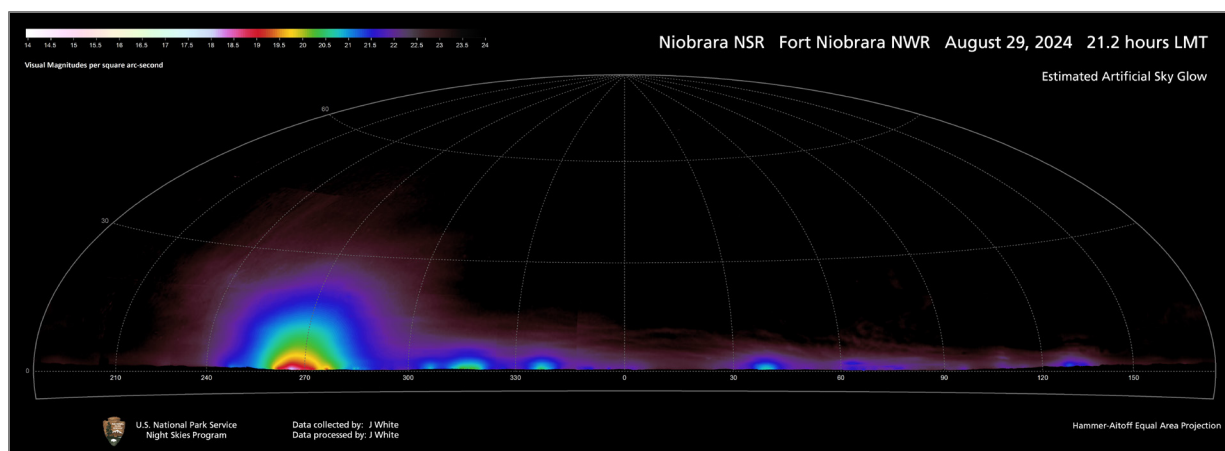


Figure 4. Panoramic image of artificial skyglow at the Fort Niobrara NWR site on August 29, 2024. The grid lines are spaced 30° apart. The image displays estimated skyglow from artificial sources. The natural light has been removed from this image, showing only the artificial skyglow and associated light domes.

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In the image from Fort Niobrara, the largest and brightest light source was from Valentine, NE at azimuth 268, and 11 km away. Other visible light domes included Sicangu Village, SD at azimuth 318, and 20 km away, Mission, SD at azimuth 340 and 52 km away, and Winner, SD at azimuth 39 and 71 km away.

In Table 3, we list the nearby cities from the Fort Niobrara NWR site for the data set collected on August 29, 2024 ranked according to their brightness predicted by Walker’s Law. As noted in the Methods chapter, because Walker’s Law is a simple model, the order of the predicted skyglow might not perfectly match the order of the imaged light dome brightness.

Table 3. Nearby cities and their predicted skyglow impact at the Fort Niobrara NWR site.

Place	Population in 2020	Distance (km)	Azimuth (degree)	Walker's Value (% above natural)
Valentine, NE	2,633	11	270	6.56
Sicangu Village, SD	276	21	318	0.14
Rosebud, SD	1,455	53	320	0.07
Winner, SD	2,921	71	39	0.07
Mission, SD	1,156	52	337	0.06
Ainsworth, NE	1,616	58	129	0.06
Antelope, SD	830	51	339	0.04
St. Francis, SD	469	50	306	0.03
Crookston, NE	71	29	281	0.02
Gregory, SD	1,221	89	63	0.02

Sky Quality Indicators

We summarize the sky quality measurements in Table 4 and Table 5. Based on the observed panoramic images, we report five indicators (Duriscoe, 2016) that focus on different aspects of sky brightness. These are horizontal illuminance, maximum vertical illuminance, zenith brightness, % of stars visible, and all-sky light pollution ratio (ALR). If multiple data sets were taken at night, we report only the measurements from the set taken under the best observing conditions and free of processing issues. The listed local date and time mark the midpoint of image acquisition. We provide bright urban sky measurements at Rock Creek Park in Washington, DC for comparison. The median natural sky (Duriscoe, 2016) is the natural reference condition against which we can compare all measured values. We complement our CCD camera observations with a visual assessment of Bortle Class and naked eye limiting magnitude (NELM) and take readings with a Unihedron Sky Quality Meter (SQM) whenever possible (Table 5).

Table 4. Niobrara National Scenic River sky brightness metrics derived from the observed images.

Date	Time (hh:mm)	Horizontal Illuminance (mlx)	Max. Vertical Illuminance (mlx)	Zenith Sky Luminance (mag/arcsec ²)	Stars Visible (%)	All-sky Light Pollution Ratio
8/29/2024	21:10	0.85	0.63	21.53	98	0.18
8/30/2024	23:05	0.86	0.56	21.7	100	0.09
Urban Sky ^A	–	39.56	29.04	18	8	64.43
Natural Sky ^B	–	0.80	0.40	22	100	0.00

^A Rock Creek Park in Washington, DC was used as the urban sky reference.

^B The median natural sky is the natural reference condition.

Table 5. Niobrara National Scenic River visual and SQM measurements.

Date	Bortle Class	Limiting Magnitude	SQM (mag/arcsec ²)
8/29/2024	2	6.8	21.41
8/30/2024	2	6.7	21.46
Urban Sky ^A	8	5.2	18.36
Natural Sky ^B	1	7	22

^A Rock Creek Park in Washington, DC was used as the urban sky reference.

^B The median natural sky is the natural reference condition.

Illuminance is the amount of visible light incident on a unit surface area. It is more sensitive to light striking closer to perpendicular to the surface. Specifically, the impact from a light source is weighted by the cosine of its angle of incidence. For example, the weighting factors for sources incident perpendicular to the surface, 60 degrees away, and 90 degrees away (parallel to the surface) are 1, 0.5, and 0, respectively.

The horizontal illuminance describes the amount of light landing on a horizontal surface. It provides the illuminance measurement of the entire sky at a glance but is not sensitive to skyglow near the horizon. From the 2 observation nights in NIOB, horizontal illuminance is only slightly higher than the natural reference. The measured horizontal illuminance values indicate the park preserves to a large extent the natural illumination on the plane.

The vertical illuminance describes the light striking a vertical surface. The vertical illuminance better reflects the brightness of sources near the horizon. Since a vertical surface can be held facing many different directions, we report the maximum vertical illuminance. Note that the maximum vertical illuminance can be greatly influenced by natural sources such as the Milky Way, zodiacal light, and airglow. From the 2 observation nights in NIOB, the maximum vertical illuminance from all sources is 0.63 mlx, which is greater than the referenced natural value of 0.40 mlx in all observations. This result shows how even low to moderate artificial lights have a measurable effect in brightening the night sky along the horizon. Nonetheless, the overall illuminance level is still low, providing a refuge for crepuscular and nocturnal species in the park.

The zenith sky brightness is measured within a 1-square degree area directly overhead. The zenith usually is the darkest part of the sky since all light domes are located along the horizon. For reference, the darkest natural sky can reach V-band brightness of 22 mag/arcsec², and the brightest part of the Milky Way is about 20 mag/arcsec². Overall, the photometric measurements in NIOB show the zenith is very dark, and skyglow at zenith is not measurable. The sky overhead remains pristine with an average zenith brightness of 21.62 mag/arcsec².

The percent visible star metric concerns the percentage of stars that are visible to the naked eye after accounting for the influence of skyglow. When calculating this metric, we have taken the atmospheric transparency and the natural sky brightness at the time of the observation into account but do not consider atmospheric turbulence, which may influence the faintest stars visible. On average, there are about 4000 stars visible to the naked eye under the natural dark sky. This metric estimates the direct impact of skyglow to human visual observation of stars and night sky features. From the 2 observation nights in NIOB, we estimate on the average, 99% of stars were still visible during data collection, providing an outstanding opportunity to observe the natural night sky from the park.

All-sky light pollution ratio (ALR) is an index of total skyglow. We calculate it by taking the total brightness from the skyglow and dividing by the brightness of the natural dark sky. We always use a constant value of 250 microcandela per square meter as the brightness of the natural dark sky in this calculation to ensure equitable comparison of ALR values across data sets. If the sky is completely free of skyglow, this ratio would be zero. Generally, ALR values less than 0.3 (30% brighter than natural) indicate excellent conditions, 0.3 to 2.0 (30–200%) indicate impaired sky quality (though areas of the sky may reveal important natural features), and greater than 2.0 (>200%) indicate the natural night sky is not readily visible. The whole sky over NIOB is 9%–18% (mean=14%) brighter than average natural levels, indicating excellent dark sky conditions.

Indicators derived from these ground-based measurements indicate only a very small amount of impact from light pollution has been measured in these sky luminance data. These indicators are supported by visual observations and assessments at the site. Bortle Class is a nine-level numeric scale that measures the night sky's brightness at a particular location based on visible sky objects (Bortle, 2001). The rating of one indicates pristine night sky that is completely free of skyglow, and nine indicates heavily light polluted sky often found in the inner cities. In NIOB, we classified 2 as the most common Bortle Class value (typical truly dark site). Airglow may be weakly apparent along the horizon. The Triangulum Galaxy, M33, is easily seen with direct vision. The summer Milky Way is highly structured to the unaided eye, and its brightest parts look like veined marble when viewed with ordinary binoculars.

Naked eye limiting magnitude (NELM) is the magnitude of the faintest star we can see in the sky with naked eyes. As the night sky brightness increases, the limiting magnitude will degrade to a lower value. The NELM will also depend on the observer and will increase with the eye's dark adaptation. A NELM of 6.6 is considered near pristine under average conditions, 7.0 is achievable under good seeing conditions and with proper dark adaptation of the eye, and 7.4 is excellent, just about the faintest attainable. A number lower than 6.3 usually indicates degraded sky quality. The limiting magnitude is also a common metric used by citizen scientists to assess the sky brightness globally. In NIOB, the average limiting magnitude is 6.75, approaching degraded sky quality.

The hand-held Sky Quality Meter (SQM-L) is an economic and convenient tool to take a single value of sky brightness measurement with just one click. We point SQM-L towards zenith when taking a reading. The SQM-L has a moderate field of view; its full width half maximum of the angular sensitivity is $\sim 20^\circ$. Although getting a reading is fast and easy, the instrument does not reliably measure the sky brightness when the sky is darker than $\sim 21.5 \text{ mag/arcsec}^2$. Measures taken at Fort Niobrara and Norden Bridge yielded an average SQM-L reading of 21.43. Due to strong airglow at Fort Niobrara and very strong Aurora activity at Norden Bridge, these values are slightly elevated. It should also be noted that the Milky Way was overhead for most of each night which can also contribute to elevated SQM values.

Regional Sky Brightness Model

Figure 5 displays park and regional predictions of skyglow based on the SALR model using the annual 2023 cloud-free composite of VIIRS data. The metric depicted is all-sky average sky brightness, expressed as a ratio of artificial to natural background. Skyglow can be seen from up to 300 kilometers away from large metropolitan areas. The map displays the park and the surrounding area, including cities within approximately 100 km. This map provides a landscape view of the average sky brightness in and around the park. The scale on the left gives the ratio between the natural and artificial light where the lower the ratio, the better the night sky viewing and lower levels of visible artificial light.

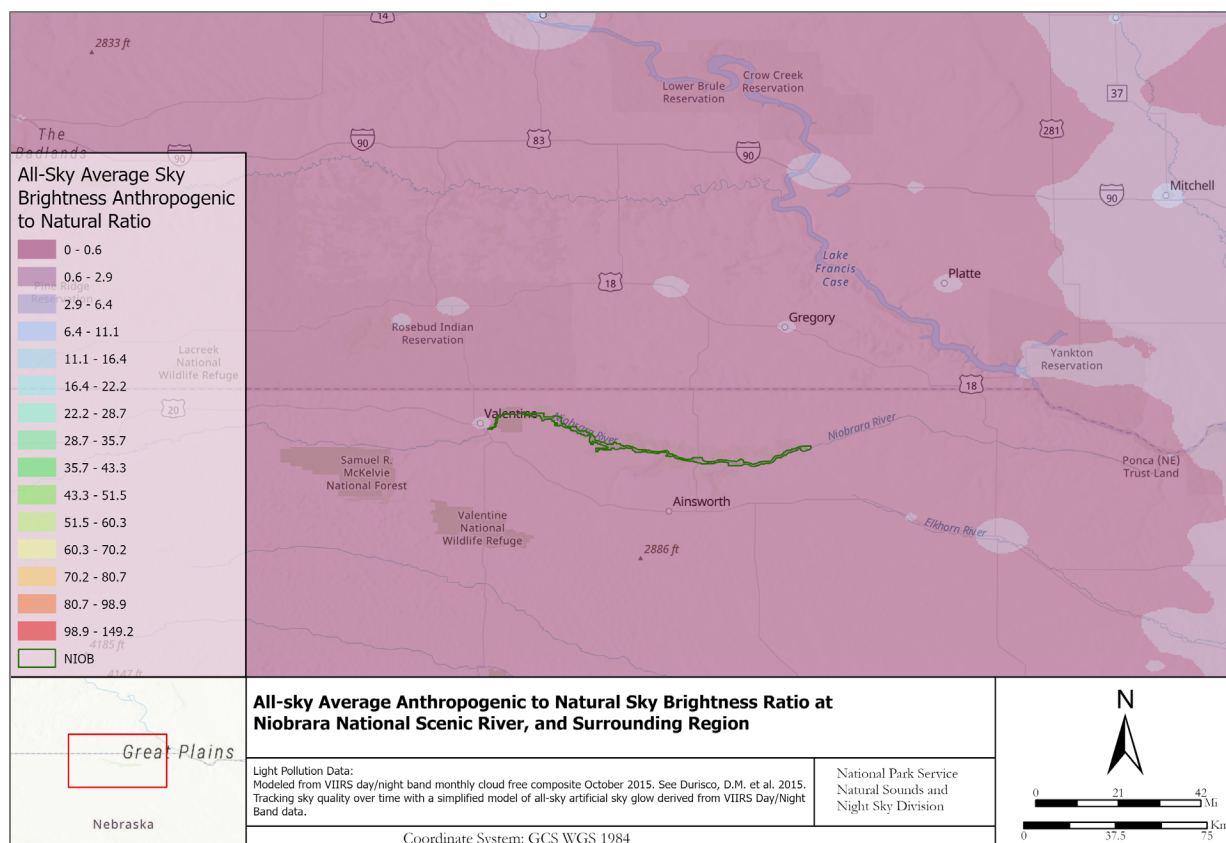


Figure 5. A model of average all-sky light pollution ratio (ALR) in the region surrounding Niobrara National Scenic River. The park boundary is outlined in green.

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NIOB is surrounded by a dark near pristine landscape with the exception of Valentine, NE and a few small communities. In the largest nearby community of Valentine, NE the sky quality is dramatically different than in the park. NIOB is mostly in purple color (values around 0.09), which agrees with all the measurements taken inside the park. At NIOB, the mean modeled ALR was 0.1 (0.06–0.53). At this average ALR, the modeled whole-park sky quality condition is considered excellent. At this light level, humans should be able to fully adapt to the dark and have an opportunity to see the Milky Way from nearly horizon to horizon, complete constellations, deep sky objects, zodiacal light, and airglow.

Discussion

Variation in Natural Sources

Variations in airglow activity can change sky brightness and complicate the assessment of sky quality. Airglow is caused by particles releasing energy in the form of light in the earth's upper atmosphere. These particles obtain the energy from the sun and cosmic rays. The sun shows an activity cycle of eleven years, and this cycle seems to correlate with the airglow brightness (Patat, 2008). While the average airglow brightness shows long-term variation, the brightness and pattern can change in minutes. Bright airglow will wash out some night sky features, such as faint galaxies and details in the Milky Way, directly affecting the visual assessment of the night sky. In addition, the indicators derived from the observed sky brightness, including the illuminance and zenith brightness, can also be affected. To account for this natural variation, we subtract airglow in our modeling process before estimating the skyglow brightness. However, the uncertainty of the associated metrics (% of visible stars and ALR values) can still be high due to the uncertainty of airglow modeling. In general, suburban skies (Bortle Class 4 and 5) are most susceptible to the large percentage error from the airglow modeling process compared to rural and urban sites. A detailed discussion about the airglow modeling uncertainty can be found in Duriscoe (2013).

Another factor that could significantly affect the skyglow measurement is the amount of aerosols in the atmosphere. Aerosols can come from natural sources (i.e., wind-borne dust, wildfire smoke, sea spray, and volcanic debris), but they can also originate from human activities (i.e., industrial emissions, fossil fuel combustion, and waste and biomass burning). From the visual observation perspective, observers will see fewer stars if the aerosol concentration is higher. From the skyglow measurement perspective, a higher aerosol level will enhance the brightness of nearby sources but diminish the brightness of distant sources. Variation in aerosol content can affect the sky brightness measurements even with no net increase in light intensity from ground-based sources. It should be noted that during each night of observations natural airglow was visible to the naked eye.

Measurement Uncertainties

The direct measurement uncertainties are about a few percent, and the uncertainty of the estimated skyglow varies from data set to data set. In the observed image mosaic, pixel-to-pixel random error in sky brightness measurement is $\pm 4\%$. Systematic error is typically less than 2% as the instrument is calibrated on standard stars for each data set. For the estimated skyglow brightness mosaic, the uncertainty largely depends on the natural sky model due to the spatial and temporal variations in the airglow brightness as discussed earlier. Duriscoe (2013) discussed these measurement uncertainties in detail. The all-sky average measurement of skyglow, such as ALR, is typically accurate to $\pm 5\%$, or 0.05 magnitudes.

Data Quality and Anomalies

A strong geomagnetic storm caused bright Aurora Borealis displays on the night of August 30 (Figure 6). The Aurora is visible on our all-sky data from Norden Bridge and affected the quality of our data. To generate light pollution metrics, we subtract out the natural sources of light such as galactic light and airglow, however we cannot model Aurora Borealis due to its highly transient

nature. We did our best to mask out most of the Aurora signal for the Norden Bridge data, however, some signal is influencing the metrics from this site. Due to its remote location, we can be confident that ALR is less than 10%, and sky quality is excellent, to near pristine.



Figure 6. Aurora Borealis lights up the night sky above Norden Bridge along the Niobrara River. The Milky Way is also easily visible to the west. This display of Northern Lights altered the night sky measurements slightly as not all of this natural signal could be subtracted out. The Valentine, NE light dome is visible along the horizon on the left side of the image.

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Glare

Glare is bright and uncomfortable light shining from the source directly to the observer. In general, common glare sources include outdoor lights from cities and developments, nearby luminaires, and car lights. Even at distances of several miles, glare can significantly degrade the view of the night sky and impair an observer's night adapted vision. Our data and visual observations from Fort Niobrara, Norden Bridge, and Mariaville Bridge indicate no direct sources of glare. From Fort Niobrara, the brightest source of light was the Valentine light dome, which exceeded the brightness of the Milky Way. Within the light dome some light sources were visible but did not create glare at the observation point. However, the visibility of these sources degraded an otherwise pristine site, and indicate these lights are unshielded or only partially shielded.

Conclusions

Overall, the night sky conditions at NIOB are excellent, and near pristine. The measured sky brightness averaged over the whole sky is only slightly brighter than the natural conditions, allowing wildlife and park visitors to experience near natural darkness at night. Along most of the Niobrara NSR, visitors can find places free of direct glare that allow for dark adaptation under a near natural sky. During clear and dark nights, visitors will have an opportunity to see the Milky Way (nearly horizon to horizon), complete constellations, deep sky objects, and fainter natural sources of light such as the zodiacal light and airglow.

In NIOB, night skies were visually classified as truly dark, based on the visibility of astronomical objects. The NELM is approaching near pristine under average conditions. Airglow may be weakly apparent along the horizon. The Triangulum Galaxy, M33, is rather easily seen with direct vision. The summer Milky Way is highly structured to the unaided eye, and its brightest parts look like veined marble when viewed with ordinary binoculars. The main impact on NIOB's night sky quality is the light dome from Valentine, NE, with smaller impacts from Ainsworth, NE, Springview, NE, Sicangu Village, SD and Winner, SD. Of these, Valentine was the largest and brightest. From Fort Niobrara, the Valentine light dome was the dominant feature of the landscape, significantly brighter than the Milky Way and any other natural feature. From Norden Bridge, the Valentine light dome was still visible, and just slightly brighter than the Milky Way, although its footprint was much smaller at that distance. While impacts from light domes and distant glare sources are low during clear nights, an increase in atmospheric aerosols can significantly alter sky brightness by amplifying the impacts of existing artificial light and further degrading the night sky quality.

Practicing sustainable outdoor lighting within the park and with the neighboring communities is a key to reducing light pollution. Sustainable outdoor lighting observes the following principles: light only if needed, light only when needed, light only where it is needed, use warm-white or amber light, use the minimum amount of light needed, and use energy-efficient lights. Locally, appropriate lighting in the park can provide visitors the optimal observing environment. Partnering with gateway communities can further reduce light pollution, both locally and regionally. Reducing light pollution improves the quality of night sky viewing. Ultimately, improving night sky quality can result in increased visitor spending in gateway communities. Preserving the natural night sky really requires a joint effort and can be mutually beneficial to all parties.

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Appendix A: Observation Notes and Panoramic Images

On 8/29/2024, at Fort Niobrara NWR: Clear night with just a scattering of clouds during twilight, clearing by night. Some high overhead smoke also clearing by night. Only one visible light dome from nearby Valentine, NE. The lightdome is bright relative to the dark surrounds, but not bright enough to impact night vision. There are three very faint sources of light, but only visible after full dark adaptation, and very close to the horizon. Milky Way is bright and detailed, visible from horizon to horizon. Some airglow visible later in the evening.

Full resolution mosaic:

https://www.nps.gov/subjects/nightskies/graphics/NIOB240830_hmrFULL.jpg

Estimated artificial sky glow:

https://www.nps.gov/subjects/nightskies/graphics/NIOB240830_hmrART.jpg

On 8/30/2024, at Norden Bridge: Aurora Borealis dominated the northern horizon. Milky Way was bright and detailed, visible almost horizon to horizon. Only one light dome visible from Valentine, NE but it was very small and extremely faint. Otherwise a pristine site with natural night sky conditions.

Full resolution mosaic:

https://www.nps.gov/subjects/nightskies/graphics/NIOB240831_hmrFULL.jpg

Estimated artificial sky glow:

https://www.nps.gov/subjects/nightskies/graphics/NIOB240831_hmrART.jpg

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