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Effect of coal-fired power generation on visibility in a nearby national park

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The Mohave coal-fired power plant has long been considered a major contributor to visibility impairment in Grand Canyon National Park. The permanent closure of the plant in 2005 provides the opportunity to test this assertion. Although this analysis, based on data from the Interagency Monitoring of Protected Environments (IMPROVE) Aerosol Network, shows that fine sulfate levels in the park dropped following the closure, no statistically significant improvement in visibility resulted. Difference-in-differences estimation was used to control for other influences. This finding has important implications for the methods generally employed to attribute visibility reductions to air pollution sources.

1. Introduction

The Mohave Power Project (MPP) is a large (1590 MW) coal-fired power plant located 90 miles southeast of Las Vegas in Laughlin, Nevada. Constructed in 1971, the plant was, for some time, the largest emitter of sulfur dioxide in the western United States. In 1998, a group of environmental advocacy organizations sued the plant's owners, alleging that its emissions of sulfur dioxide and particulate matter were in violation of the Clean Air Act. Approximately one year later, the plant was identified as a major cause of visibility impairment in Grand Canyon National Park (GCNP) by the U.S. Environmental Protection Agency (EPA). Upon completion of a multi-year study referred to as Project MOHAVE (Pitchford et al., 1999), the EPA concluded that, although other sources contribute to the visibility reduction, "[because] of the quantity of SO_2 emitted from the Mohave Generating Station and its proximity to the Grand Canyon, no other single emissions source is likely to have as great an impact on visibility in the Park".

A few months after this determination, the plant's owners settled the lawsuit and entered into a consent decree which required the plant to reduce SO_2 emissions no later than 2005 (Consent Decree, 1999). Subsequently, the owners estimated that additional emissions controls would cost more than $1 billion and elected to close the plant on December 31, 2005 rather than make such an investment. Over four years have passed since the closure, and we now have the opportunity to determine whether, in the prolonged absence of plant operations, air quality in the Grand Canyon has improved.

2. Literature review

The link between Mohave emissions and air quality in the Grand Canyon has been studied and debated for over 20 years, resulting in a large body of published research. The most comprehensive study to date, termed Project MOHAVE (Measurement of Haze and Visual Effects) (Pitchford et al., 1999), was performed by the EPA at the request of Congress. This multi-year research effort included two intensive tracer/receptor field experiments, several source emissions simulations and a number of related statistical analyses, all designed to definitively elucidate how MPP operation affected the atmosphere in GCNP.

Despite these considerable efforts, Project MOHAVE's conclusions are ambiguous. Tracer studies revealed that MPP emissions did reach the park, particularly in the summer, when tracer concentrations were recorded above background levels on 90% of the days at the park's western edge. However, there was no evidence linking these elevated concentrations with actual visibility impairment; indeed, "correlation between measured tracer concentration and both particulate sulfur and light extinction were virtually nil" (Pitchford et al., 1999, p. iii). Tracer data also indicated that "primary particles from MPP disperse during transport to GCNP to the extent that though they contribute to visibility impacts

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they alone would not cause noticeable impairment" (p. v). Overall, the combined results from the tracer studies "strongly suggest[ed] that other sources [than MPP] were primarily responsible for the haze" (p. v).

In contrast to these measurements, pollution transport simulations such as HAZEPUFF (Latimer, 1993), CALPUFF (Scire et al., 2000), and RAPTD/HOTMAC (Williams et al., 1989) did suggest a negative relationship between MPP emissions and visibility. According to these models, MPP contributed between 8.7% and 42% of measured sulfate on the 90th percentile worst air quality days at the western edge of the Canyon, and 3.1–13% of sulfate on the south rim. In terms of visibility, the models showed that MPP increased light extinction by 1.3–5.0% at the western edge of the canyon and 0.5–2.6% on the south rim. The predicted effect at the 50th percentile was lower in each case, suggesting that MPP impaired visibility most on days when air quality was already quite poor.

Noting the disconnect between the measurements and model predictions, EPA observed that "empirical data (actual field measurements) show poor correlation between the presence of MPP tracer and visibility impairment in the GCNP. Project MOHAVE analysts were unable to find any data to directly corroborate the extreme values calculated by some of the models …" (Pitchford et al., 1999, p. x). Based on these findings, EPA concluded that MPP was the largest sole contributor to visibility impairment in GCNP. Emissions from large urban areas in California, Arizona and northwestern Mexico were also judged to have contributed significantly (Environmental Protection Agency, 1999).

Subsequent analyses which used CALPUFF to model the transport of MPP emissions to GCNP obtained similar results. A Best-Available Retrofit Technology (BART) Assessment[1] conducted for Southern California Edison used CALPUFF to estimate the visibility impact of retrofitting Mohave as a natural gas-fired plant (Paine and Kostrova, 2008). Model results predicted that retrofitting MPP to burn natural gas instead of coal would result in an improvement of approximately 2 deciviews (a standard unit of visibility measure; see below) in the top 2% annual worst air quality days. Additionally, it was estimated that MPP reduced visibility at least 0.5 dv on approximately 500 days over three years. Another CALPUFF analysis conducted by the State of Nevada found that the 98% percentile improvement would be 2.4 dv and that there would be 186 fewer days annually where the MPP effect would be greater than 0.5 dv (Nevada Division of Environmental Protection, 2009).

Independent reanalyses of the Project MOHAVE tracer data suggest a small or nonexistent Mohave effect. Kuhns et al. (1999) used tracer concentrations during the summer intensive to identify areas which were unaffected by the Mohave plume, and hence only subject to regional changes in sulfate. After controlling for this regional component, they found that MPP was responsible for $7 \mp 3\%$ of the particulate sulfur deposited in the western portion of GCNP; the single largest daily contribution was estimated at $0.286 \mp 0.9\ \mu g\ m^{-3}$. Mirabella and Farber (2000) found evidence of a strong regional sulfate component but almost no correlation between local tracer and sulfate concentrations. Eatough et al. (2000) estimated that MPP emissions contributed only 4.3–5.5% of total sulfate in GCNP; the principal sources of sulfate were surrounding urban areas such as Las Vegas, Los Angeles and the San Joaquin Valley. Later, Eatough et al. (2006) determined that the Los Angeles and Las Vegas urban areas were also the main causes of light extinction in GCNP, and that MPP-associated emissions contributed negligibly.

Two earlier papers have used a disruption in plant operations to identify MPP's effect on Grand Canyon air quality. First, Murray et al. (1990) examined a seven-month plant closure in 1985 and found no effect on ambient sulfate concentrations in GCNP during the shutdown. They concluded that MPP was responsible for less than 3% of sulfate at the south rim of the canyon. Switzer et al. (1996) expanded on this study by examining monitoring data for the summers of 1985–1987, a period which included both the seven-month shutdown as well as numerous partial shutdowns that occurred when one or both of the plant's two generating units were temporarily offline. By comparing these daily variations in plant operations with simultaneous sulfate measurements taken in GCNP, any link between MPP emissions and GCNP air quality would potentially be cast into greater relief. Despite this added variation, the authors were again unable to detect any statistically significant effect.

There is some evidence that GCNP air quality responded positively to a decrease in emissions from another nearby power plant. Between 1997 and 1999 three scrubbers were installed at the Navajo Generating Station (NGS), a 2250 MW coal-fired facility located on the eastern edge of GCNP. Analyzing the resulting 90% decrease in emitted SO_2, Green et al. (2005) found that the upper percentiles of the sulfur and light extinction distributions fell following the installation of all three scrubbers. A chi-squared test for independence was used to show that the percentage of winter days exceeding a pre-set threshold for particulate sulfate fell by a statistically significant amount. The authors concluded that reducing NGS emissions decreased winter haze and improved visibility in the park.

3. Model

Since prior research is ambiguous regarding the impact of MPP on GCNP air quality, it is useful reinvestigate this relationship taking advantage of the prolonged plant closure and the availability of data to control for weather, background trends in air quality, human activity and other factors which could have affected contemporaneous visibility. A rigorous statistical model is also needed in order to isolate the air quality improvement attributable to emissions reductions.

Consider a two-period model of air quality at a network of regional monitoring sites in the presence of a power plant shutdown. The air quality outcome (light extinction, visibility, pollutant concentration, etc.) at monitoring site $i \in \{1, \ldots, n\}$ in period $t \in \{0, 1\}$ is denoted $y_{i,t}$. Air quality at each site and time period is governed by several factors. The first is a regional component R_t which, as the subscript suggests, varies over time but affects all sites equally. Examples of such effects include mesoscale meteorological conditions and pollution transported into the region from large urban areas, as appears to be the case on the Colorado Plateau.

A second component, denoted S_i, captures time-invariant, site-specific effects, which would include elevation and proximity to localized pollution sources whose emissions profiles are relatively constant over time. Finally, emissions from a nearby power plant affect only some of the sites in period 0. Let δ denote this effect, and let $P_{i,0} = 1$ if site i was affected by the plant. The plant closes between the periods 0 and 1, so $P_{i,1} = 0$ for all i. In the treatment effects literature, the group $C := \{i \in \{\{1, \ldots, n\}\} : P_{i,0} = 0\}$ is known as the "control" group and $T := \{i \in \{1, \ldots, n\} : P_{i,0} = 1\}$ the "treated" group, and the effect of the plant closure is the treatment effect.

Assuming these components are additive, the air quality outcome at site i in period t is then

$$y_{i,t} = R_t + \delta P_{i,t} + S_i + \nu_{i,t}, \qquad (1)$$

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[1] As part of the Regional Haze Rule, EPA requires certain power plants constructed between 1962 and 1977 to install the Best-Available Retrofit Technology (BART) in order decrease their emissions of haze-forming pollutants.

where $v_{i,t}$ is an error term which is assumed to have zero mean overall i and t. In this model, we only observe $y_{i,t}$ and $P_{i,t}$, and are interested in estimating δ, the effect of the plant operation on the affected sites. Model (1) may be estimated by least squares provided the identifying assumption

$$\mathbb{E}(v_{i,t}|R_t, P_{i,t}, S_i) = 0 \tag{2}$$

holds. In particular, this requires that δ would be zero for the "treated" sites if the closure had not occurred, and that there are no omitted idiosyncratic covariates.

In econometrics, the OLS coefficient $\hat{\delta}$ is known as the difference-in-differences estimator because it is computationally identical to the difference in mean outcome change between the treated and control groups:

$$\hat{\delta} \equiv \overline{\Delta y}_C - \overline{\Delta y}_T, \tag{3}$$

where $\Delta y_i = \Delta R - \delta P_{i,0} + \Delta v_i$.

This model generalizes to multiple time periods and heterogeneous treatment effects, and additional covariates can (and should) be added to ensure assumption (2) holds. In the air quality arena, this approach has been previously applied to study the effect of pollution regulation on firm location (Millimet and List, 2004; List et al., 2003), particulate matter concentrations on infant mortality (Jayachandran, 2009), air pollution on school absences (Currie et al., 2009), air quality advisories on public transit use (Cutter and Neidell, 2009), and similar policy questions. Previous studies which used spatial or temporal variations in MPP's output as an instrument for GCNP air quality (Murray et al., 1990; Switzer et al., 1996; Kuhns et al., 1999) also employ essentially the same technique, provided the GCNP outcomes are compared with nearby unaffected areas. Conversely, we contend that trend analyses which simply examine air quality over time misidentify the Mohave effect by failing to remove latent regional components and/or control for idiosyncratic effects.

4. Data

We studied the Mohave effect using the above model and a high-frequency, heterogeneous panel of air quality data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) Aerosol Network. The network consists of remote sensing stations located in EPA Class 1 visibility areas, which are primarily national parks and wilderness areas. IMPROVE is EPA's designated data source for measuring air quality under the Regional Haze Rule.[2]

Data are collected every three days, and most of the sites have at least ten years of historical observations available, including three years of data collected after the Mohave closure. The data consist of measurements of sulfate, nitrate, and other aerosol concentrations.[3] IMPROVE composites these measurements into a standard index of visibility known as the deciview (dv) (Pitchford and Malm, 1994). The deciview is analogous to the decibel unit of noise measurement; it is approximately linear with respect to perceived changes in visibility, and higher values signify increased degradation. A one-unit decrease in deciviews represents a small but perceptible improvement in visibility. The deciview is the primary metric of the Regional Haze Rule.[4] IMPROVE monitoring sites also include a log which notes maintenance events as well as external anomalies which could perturb the measurements. We used these logs to build an auxiliary panel of anomalous events for control purposes.

Censoring was performed on the IMPROVE time series to ensure representativity. We used daily surface wind direction and speed measurements taken at Laughlin/Bullhead City Airport, located 3 miles east of MPP, to isolate days when the wind blew from the south and southwest, directing the Mohave plume towards GCNP. A mid-level wind measurement is preferable to surface wind data when modeling plume transport, but the two should be sufficiently correlated for our purposes. Also, we excluded observations taken on days when the National Weather Service issued warnings concerning dust storm activity in northern Arizona to avoid confounding the visibility measures.

To control for cloudiness and its effect on sulfate formation, daily satellite imagery from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) program was used to calculate cloud albedo on a 0.5 × 0.5-degree (latitude × longitude) grid. To control for wildfires, a separate MODIS product was used to determine fire activity. These pixel-level data were interpolated over the study area using density estimation to model smoke effects. Finally, we used data on monthly generation at individual power plants in the southwest to examine how regional power generation responded to the Mohave Closure. These data were derived from the U.S. Energy Information Administration's Form EIA-920 database.

5. Analysis

There are three IMPROVE monitoring sites in or near the Grand Canyon. Indian Gardens is 3 km from the south rim at an elevation of 1166 m, approximately one quarter of the distance from the Colorado River to the upper rim of the canyon. Hance Camp is almost directly above Indian Gardens, on the edge of the south rim at nearly twice the elevation (2267 m). Meadview overlooks the southern shore of Lake Mead on the western edge of the park. It is 20 km from the mouth of the Grand Canyon and 107 km from MPP.

Project MOHAVE tracer studies suggest areas which were near Mohave but unaffected by its plume (Green, 1999). Several of these areas have IMPROVE monitoring stations, and they form the basis for comparing air quality outcomes in GCNP. The particular sites used as the control group were Ike's Backbone, Petrified Forest and Queen's Valley. The sites are 100–300 km distant from GCNP. Since these sites are southeast of Mohave, they are unlikely to have been affected by MPP operation, particularly in the summer.

5.1. *Descriptive statistics*

Descriptive statistics for the IMPROVE data are shown in Tables 1 (deciviews), 2 (light extinction) and 3 (fine sulfate). The first three rows consider the three GCNP sites, followed by nearby control sites in rows four through six. The final rows show monitoring data for sites located in Phoenix and east of Southern California (Agua Tibia Wilderness); as transported urban pollution is believed to strongly influence air quality on the plateau, it is wise to examine how these donor areas performed over the same time period. Columns one through four show mean visibility for the entire study period, the pre-closure period 2003–2005, the post-closure period 2006–2008, and the difference in means between the two periods. Comparing the

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[2] The Regional Haze Rule (40 CFR 51), promulgated in 1999 by the U.S. EPA to meet Clean Air Act requirements, is designed to improve air quality in general and visibility in particular at 156 national parks and wilderness areas. The Rule obligates the States, in coordination with federal agencies such as the U.S. Forest Service and the National Park Service, to develop and implement plans to improve visibility by 2008.

[3] The specific data set we used was entitled, "IMPROVE Aerosol, RHR (New Equation)." For lack of a better term, we refer to these data as "daily" even though they are not sampled every day.

[4] In 2006 the IMPROVE Steering Committee adopted a revised algorithm for calculating visibility. The revised estimates were used in this study.

Table 1
Descriptive statistics for daily visibility, 2003–2008.

Outcome: dv	2003–2008 (1)	2003–2005 (2)	2006–2008 (3)	Δ (4)	SD (5)	N (6)	Missing (7)
Meadview	8.24	8.23	8.24	0.00	3.06	659	68
Indian Gardens	8.92	8.86	8.96	0.10	3.66	614	113
Hance Camp	6.54	6.61	6.47	−0.14	3.58	695	32
Petrified Forest	8.76	9.12	8.39	−0.73	3.38	628	99
Queen Valley	11.62	11.73	11.50	−0.23	3.01	648	79
Ike's Backbone	9.36	9.46	9.26	−0.21	3.14	698	29
Phoenix	18.04	18.61	17.40	−1.22	4.39	618	109
So. Cal.	15.90	16.25	15.55	−0.69	5.01	592	135

between-group differences in column four is analogous to (3) and hence estimates how the closure altered air quality in GCNP after controlling for other sources of variation.

Average visibility (Table 1) was unchanged at Meadview after the closure; a slight improvement was noted at the upper south rim (Hance Camp); and Indian Gardens worsened slightly. Meanwhile, the control group sites improved by 0.21–0.73 dv. Visibility at sites in Phoenix and Southern California also improved perceptibly post-closure, by 1.22 dv and 0.69 dv respectively. Similar patterns are seen in light extinction (Table 2). Light extinction fell at every monitoring site in the region compared with before the closure. Large improvements occurred in Phoenix and Southern California, while the control sites also improved by lesser amounts. Despite the shutdown, Meadview actually witnessed the least change in light extinction.

Fine sulfate concentrations (Table 3) exhibit a more marked difference between GCNP and surrounding areas. A large drop in SO_4 (-0.11 μg m^{-3}) was registered at Meadview, while other sites within the canyon were essentially unchanged. Smaller changes in sulfate concentration were registered at the control sites. Finally, sulfate levels in the surrounding urban areas also fell by a significant amount; in particular, the percent improvement in the Southern California region roughly equals that witnessed at Meadview.

Arizona and Southern California are major sources of pollution in the Grand Canyon area. At the same time, they are both distant from and generally upwind of Mohave and hence should not have been affected by the closure. These observations lead us to suspect that visibility improved throughout the region from 2003 to 2008, and that GCNP may have benefited from a drop in transported pollution from surrounding urban areas over that time.

One conclusion of the Project MOHAVE report is that MPP operation was most detrimental to the Grand Canyon on days when air quality was already very poor. If so, the closure effect would be more pronounced at the upper tail of the air quality distribution, for example by decreasing the frequency of days with extremely low visibility. Following Green et al. (2005), Fig. 1 shows empirical cumulative distribution plots for fine sulfate at Meadview. For clarity, only the 70th through 99th percentiles are shown. The upper percentiles for fine sulfate at Meadview dropped approximately 0.2 μg m^{-3} following the closure, and extreme events appear to have lessened by varying degrees in each plot. Similar results (not shown) were encountered for Hance Camp and Indian Gardens.

Fig. 2 repeats the same plot for the Southern California monitoring station. A similar pattern of improvement emerges even though this site is too far from Mohave to have benefited from the plant closure. This again suggests that regional air quality was improving when the shutdown took place, and underscores the need for a more comprehensive analysis to identify the precise effect of the closure on GCNP.

5.2. *Average effect*

Specification (4) is a standard generalization of the two-period difference-in-differences estimator to multiple time periods and sites:

$$\begin{aligned} y_{i,t} = {} & \beta_0 + \boldsymbol{\beta_t} + \boldsymbol{\beta_i} + \beta_1 \mathrm{FIRE}_{i,t} + \beta_2 \mathrm{CLOUD}_{i,t} \\ & + \beta_3 \mathrm{ANOMALY}_{i,t} \boldsymbol{\delta}(\mathrm{SITE}_i \times \mathrm{CLOSURE}_t) \\ & + \boldsymbol{\gamma}(\mathrm{SITE}_i \times \mathrm{CLOSURE}_t \times \mathrm{SUMMER}_t) + \varepsilon_{i,t} \end{aligned} \tag{4}$$

The subscripts i and t index monitoring sites and time (days), respectively. The outcome variable $y_{i,t}$ is deciviews, sulfate or light extinction, as measured by IMPROVE. Vectors $\boldsymbol{\beta_t}$ and $\boldsymbol{\beta_i}$ capture site- and time-level fixed effects, GCNP_i and $\mathrm{CLOSURE}_t$ are dummy variables for the Grand Canyon monitoring sites and post-closure days. $\mathrm{FIRE}_{i,t}$ is a unit-less parameter derived from the MODIS fire product. $\mathrm{ANOMALY}_{i,t}$ is an indicator variable equal to one if the site's log noted an anomaly on that day. $\mathrm{CLOUD}_{i,t}$ is cloud albedo, as measured by the MODIS daily high-resolution cloud product. $\varepsilon_{i,t}$ is an error term. Vectors $\boldsymbol{\gamma}$ and $\boldsymbol{\delta}$ represent the net effect of the closure on each GCNP monitoring site in the summer and in the remainder of the year, respectively.

We estimated this specification by multiple regression on a balanced panel of daily data spanning six years (2003–2008, inclusive). Estimation results are reported in Table 4. A Durbin–Watson test showed strong evidence of temporal autocorrelation in the error terms, so the reported standard errors are heteroskedasticity and autocorrelation consistent. The three

Table 2
Descriptive statistics for daily aerosol light extinction, 2003–2008.

Outcome: b_{ext}	2003–2008 (1)	2003–2005 (2)	2006–2008 (3)	Δ (4)	SD (5)	N (6)	Missing (7)
Meadview	13.93	13.94	13.93	−0.02	8.18	659	68
Indian Gardens	16.41	16.69	16.18	−0.50	14.20	614	113
Hance Camp	11.77	12.38	11.13	−1.25	11.20	695	32
Petrified Forest	16.83	18.57	15.05	−3.52	15.30	628	99
Queen Valley	22.55	23.05	22.03	−1.03	11.90	648	79
Ike's Backbone	16.86	17.36	16.39	−0.97	9.63	698	29
Phoenix	56.70	61.32	51.47	−9.85	36.80	618	109
So. Cal.	44.24	46.56	41.97	−4.59	27.29	592	135

Table 3
Descriptive statistics for daily fine sulfate, 2003–2008.

Outcome: SO_4	2003–2008 (1)	2003–2005 (2)	2006–2008 (3)	Δ (4)	SD (5)	N (6)	Missing (7)
Meadview	1.17	1.22	1.11	−0.11	0.75	659	68
Indian Gardens	1.02	1.02	1.01	−0.00	0.63	614	113
Hance Camp	0.86	0.87	0.85	−0.01	0.55	695	32
Petrified Forest	1.07	1.09	1.04	−0.04	0.61	628	99
Queen Valley	1.48	1.51	1.46	−0.05	0.83	648	79
Ike's Backbone	1.14	1.12	1.16	0.04	0.70	698	29
Phoenix	1.59	1.63	1.54	−0.09	0.80	618	109
So. Cal.	2.49	2.60	2.38	−0.22	1.79	592	135

columns of estimates use sulfate, aerosol light extinction and deciviews as the outcome.

Fire is positively associated with degraded visibility but was not found to be significant. Cloud albedo was also not significant. We suggest that this is because the effect of cloudiness on sulfate formation is largely absorbed by the daily dummy variables. The closure induced drops in sulfate concentrations at all three monitoring sites in the summer. The largest decrease was experienced at Meadview, where sulfate dropped 0.318 μg m^{-3} on average. The next-largest decrease occurred at Indian Gardens and measured 0.256 μg m^{-3}. Finally, Hance Camp improved by 0.194 μg m^{-3}. The ordering of the coefficients is consistent with the notion that MPP pollution enters GCNP over Meadview, is funneled through the canyon towards Indian Gardens, and has the least impact on the upper rim at Hance Camp. No change was detected in the winter months (October–April) at any location.

Turning to the visibility measures, results show that these reductions in sulfate failed to translate into improved visibility in GCNP. The only statistically significant change in visibility was a 3.346 M m^{-1} decrease in light extinction at Hance Camp. There was no change in deciviews in the summer or winter at any of the three sites. To see if an increase in some other component could have masked the potential improvement resulting from the closure, we estimated specification (4) for every air quality component used to calculate light extinction and deciviews. We found statistically significant alterations in two components, nitrate and coarse mass. Summer nitrate concentrations fell by approximately 0.12 μg m^{-3} at Indian Gardens and Hance Camp; no change was detected at Meadview. Coarse mass increased by approximately 2.1 μg m^{-3} at all three sites after the closure.

5.3. Distributional effect

Discussion of MPP's effect on GCNP is often couched in terms of its effect on the given quantiles of the air quality distribution. The above regressions suggest this effect by isolating periods when wind and season favor poor air quality, but it is also useful to estimate it directly using a quantile regression (Koenker, 2005). Unfortunately, large cross-sectional models such as ours pose theoretical and computational challenges for existing quantile regression techniques (Koenker, 2004). To alleviate these problems, we estimated a simpler version of specification (4). We used only summer data, and the GCNP sites were pooled into a single treatment group. Month fixed effects were used instead of day fixed effects. The two-step estimator suggested by (Canay, 2010) was employed to allow for quantile-invariant individual fixed effects.

Regression results are reported in Table 5. The MPP closure resulted in median sulfate levels in GCNP falling by 0.103 μg m^{-3}. At the 90th percentile, the change increased to 0.144 μg m^{-3}. We found that median light extinction increased by 2.6 M m^{-1} after the

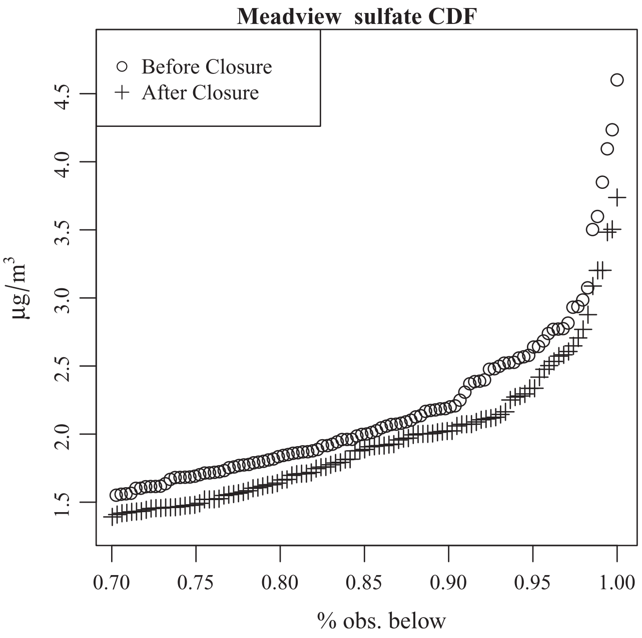

Fig. 1. Empirical cumulative distribution of fine sulfate at Meadview. Plot is of the upper 30 percentiles only.

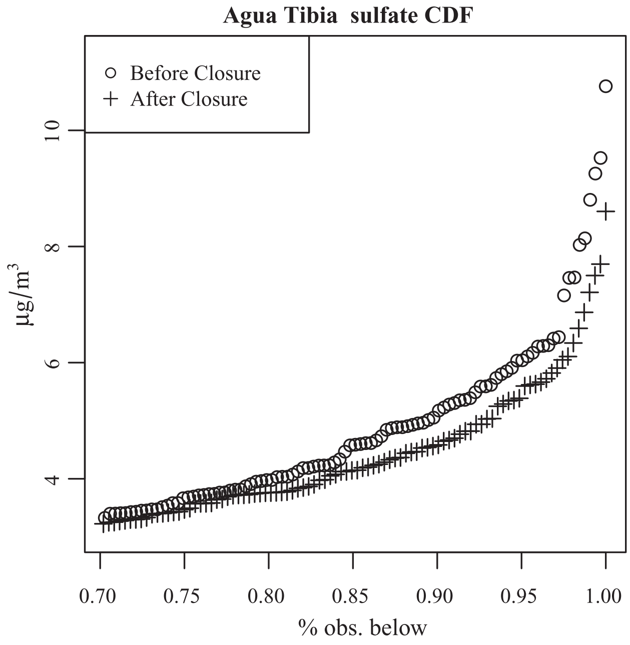

Fig. 2. Empirical cumulative distribution of fine sulfur at Agua Tibia wilderness area. Plot is of the upper 30 percentiles only.

Table 4
Difference-in-differences estimate of the effect of Mohave operation on Grand Canyon air quality.

	SO_4	b_{ext}	dv
(Intercept)	1.512^{***} (0.176)	21.717^{***} (4.086)	11.073^{***} (1.023)
Fire	0.001 (0.002)	0.090 (0.069)	0.014 (0.012)
Anomaly	-0.173^{*} (0.087)	13.673 (9.975)	3.313 (1.897)
Cloud Albedo	-0.001^{*} (0.000)	0.003 (0.006)	0.001 (0.002)
Meadview × Closure	−0.004 (0.068)	0.211 (0.935)	0.120 (0.359)
Meadview × Closure × Summer	-0.318^{**} (0.116)	0.484 (1.566)	0.118 (0.490)
Hance Camp × Closure	0.071 (0.046)	0.786 (0.865)	0.458 (0.351)
Hance Camp × Closure × Summer	-0.194^{**} (0.073)	-3.346^{*} (1.675)	−0.918 (0.489)
Indian Gardens × Closure	0.112^{**} (0.042)	1.839 (0.975)	0.672^{*} (0.339)
Indian Gardens × Closure × Summer	-0.256^{***} (0.074)	−4.539 (2.871)	−0.939 (0.530)
adj. R^2	0.790	0.476	0.679
F	21.096	5.719	11.978
$P(>\|F\|)$	0.000	0.000	0.000
N	1601	1556	1556

Significance levels: $^{***} = 0.001$ $^{**} = 0.01$ $^{*} = 0.05$.

closure, but was unchanged at the 90th percentile. Similarly, overall visibility worsened by 0.52 dv at the median, but was unchanged at the 90th percentile. Fire had a large, negative effect in air quality in several of the regressions, as did the anomaly indicator variable.

6. Discussion

The Mohave closure decreased fine sulfate concentrations in GCNP. Several different estimations found a statistically significant reduction when compared with nearby sites which were not exposed to MPP emissions. The range of our estimates, – 0.10–0.32 $\mu g\ m^{-3}$ in the summer, corresponds to approximately a 3–10% drop in sulfate, which is in line with Project MOHAVE predictions and earlier estimates of the Mohave sulfate component.

However, we found no corresponding improvement in deciviews or light extinction. This is partially explained by fluctuation in other aerosols masking the drop in sulfate. It is also possible that the sulfate change is too small relative to natural daily variation in visibility conditions to have a significant impact. In the hypothetical case that every component except sulfate remained constant after the closure, analysis of the underlying equations provides some sense of how visibility would have responded. The IMPROVE light extinction equation is (Pitchford et al., 2007):

$$\begin{aligned} b_{ext} = {} & f_S(\mathrm{RH})\left(2.2 \times \mathrm{SO}_4^S + 2.4 \times \mathrm{NO}_3^S\right) + f_L(\mathrm{RH})\left(4.8 \times \mathrm{SO}_4^L \right. \\ & \left. + 5.1 \times \mathrm{NO}_3^L\right) + 2.8 \times \mathrm{OM}^S + 6.1 \times \mathrm{POM} + 10 \times \mathrm{EC} \\ & + \mathrm{Soil} + 1.7 \times f_{SS}(\mathrm{RH}) \times \mathrm{SeaSalt} + 0.6 \times \mathrm{CM} \\ & + \mathrm{RS} + 0.33 \times \mathrm{NO}_2, \end{aligned} \tag{5}$$

where $f(\mathrm{RH})$ is a relative-humidity correction factor, POM measures particulate organic material concentration, EC measures light-absorbing carbon, Soil measures fine soil, CM measures coarse mass, and SO_4 and NO_x measure the relevant oxides. The S and L sub/superscripts denote small- and large-particle concentrations, which for SO_4 are given by ${SO_4}^L = (SO_4)^2/20$ and ${SO_4}^S = SO_4 - {SO_4}^L$. Combining these identities and equation (5) gives

$$\frac{\partial b_{ext}}{\partial \mathrm{SO}_4} = 2.2 f_S(\mathrm{RH})\left(1 - \frac{\mathrm{SO}_4}{10}\right) + 4.8 f_L(\mathrm{RH})\frac{\mathrm{SO}_4}{10}.$$

With average summer values for Meadview ($f_S(\mathrm{RH}) = 1.385$; $f_L(\mathrm{RH}) = 1.267$; $SO_4 = 1.633$), we have that a 0.20 $\mu g\ m^{-3}$ decrease in sulfate results in a 0.71 $M\ m^{-1}$ decrease in light extinction. Using the deciviews formula

$$\mathrm{dv} = 10 \times \ln\left(\frac{b_{ext+S_R}}{10}\right), \tag{6}$$

with site-specific Rayleigh scattering constant $S_R = 10\ M\ m^{-1}$ for Meadview, this translates to an improvement of roughly 0.25 dv at an average light extinction level (28.22 $M\ m^{-1}$). Assuming a 0.7 $\mu g\ m^{-3}$ decrease in fine sulfate – much higher than suggested by previous studies, and over twice as large as the greatest change we encountered – gives an expected visibility improvement of .92 dv. Hence, conservatively speaking, we believe it is unlikely that the Mohave closure would have resulted in a visibility improvement in excess of 1 dv (other factors unchanged.)

It is prudent to ask whether any GCNP-specific exogenous increase in sulfur occurred after the closure; if so, our estimates would be downward-biased. One potential source of SO_2, fire, is controlled for in the model. Another source is power generation. Did a nearby power plant (for example, NGS) increase generation to compensate for the Mohave closure? We examined federal regulatory records of monthly power generation for other plants within 300 km of the Grand Canyon before and after the closure and found no indication of such a surge. After taking seasonality into account, regional power generation (excepting Mohave) peaked in 2005,

Table 5
Difference-in-differences estimate of the effect of Mohave operation on median and 90th percentile air quality in Grand Canyon.

Outcome: τ	SO_4		b_{ext}		dv	
	50%	90%	50%	90%	50%	90%
(Intercept)	−0.064 (0.142)	0.894^{***} (0.139)	−1.991 (1.850)	19.121^{**} (7.300)	0.243 (0.520)	4.760^{***} (0.915)
Fire	0.002 (0.007)	0.004^{*} (0.002)	0.379^{***} (0.079)	0.407 (0.485)	0.075^{***} (0.010)	0.096 (0.128)
Anomaly	−0.002 (0.177)	-0.324^{*} (0.163)	3.334 (2.494)	15.452^{*} (7.438)	1.104 (0.884)	3.335 (2.492)
Cloud Albedo	0.001^{***} (0.000)	0.000 (0.001)	0.004 (0.004)	−0.011 (0.007)	0.002 (0.001)	−0.001 (0.002)
GCNP × Closure	-0.103^{*} (0.045)	-0.144^{*} (0.069)	2.597^{***} (0.555)	0.690 (1.084)	0.519^{*} (0.209)	0.034 (0.307)
N	1683	1683	1631	1631	1631	1631

Significance levels: $^{***} = 0.001$ $^{**} = 0.01$ $^{*} = 0.05$.

and trended slightly downwards for the remainder of the study period. Additionally, a followup EPA study of the Mohave closure noted that "[most] of the electricity production lost due to the closure of the Mohave Generation Station has been replaced by new natural gas-fired generation, particularly in Nevada" (U.S. Energy Information Administration, 2009). As the combustion of natural gas releases approximately 1% of the SO_2 of a comparable coal-fired plant (on an MWH basis), there is little possibility that this could have offset the effect of the closure.

Tourism in GCNP is another potential idiosyncratic source of pollution, but again the data do not indicate a countervailing effect. Monthly attendance figures from the National Park Service show that seasonally-adjusted attendance in GCNP was relatively stable from 2003 through 2008. There is no evidence that visits spiked in the years following the MPP closure, as would be required to bias the estimators.

Our results indicate that other components of visibility, in particular coarse mass and nitrate, changed in GCNP after the closure. Soil is known to be the main component of coarse mass in the Grand Canyon (Malm et al., 2007), leading us to hypothesize that dust anomalies in and around GCNP in the years following the closure might have caused visibility to worsen. To the extent that these are ignored by the controls we introduced, this constitutes an omitted variable in our model. The creation of a high-resolution dust measurement data source would advance our ability to study air quality changes over time in the southwest. Since dust is also a byproduct of driving, specific data on regional vehicle activity is also desirable.

These difficulties are indicative of a larger problem encountered when attempting to conduct inference on a calculated parameter (like deciviews) which is itself a function of many stochastic processes, each governed by a unique set of anthropogenic and natural factors. Achieving identification (in the sense of assumption (2)) will generally be much harder than when considering any one parameter in isolation. To the extent that the MPP shutdown mainly affected a single aerosol (SO_4) which has a strong regional component and is relatively stable over time, we are most confident that the sulfate effect is correctly identified.

7. Conclusion

In this paper we studied how operation of the Mohave Power Plant affected air quality in the Grand Canyon. We compared pre- and post-closure visibility in the Canyon and at nearby unaffected sites in order to identify the level of degradation attributable solely to MPP. After controlling for the prevailing environmental and anthropogenic factors in the region, we found virtually no evidence that the MPP closure improved visibility in the Grand Canyon; or, equivalently, that the plant's operation degraded it. Mean visibility (deciviews) and light extinction in GCNP did not respond to the closure in a statistically significant fashion. Sulfate levels did drop throughout the park, but not by an amount sufficient to induce a perceptible improvement in visibility.

We are thus unable to conclude that the closure improved visibility in the Grand Canyon. Our findings are consistent with, and indeed were predicted by, the results of tracer/receptor analyses performed over the past two decades, which consistently noted low correlation between MPP emissions and GCNP visibility. They stand in contrast to the various atmospheric transport models employed by Project MOHAVE, which predicted that visibility would have improved by 5% or more after the closure.

Since recent applications of CALPUFF (Nevada Division of Environmental Protection, 2009; Paine and Kostrova, 2008) continue to predict that retrofitting MPP will improve visibility in the Grand Canyon, our results raise questions about the reliability of CALPUFF. These concerns are especially pertinent in light of EPA's designation of CALPUFF as the preferred model for assessing the effects of long-range pollution transport on air quality in Class I visibility areas under the Regional Haze Rule.

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