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Predicting Economic Activity Using Atmospheric NO2 Satellite Data: Evidence from Local Economic Indicators in Japan

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Abstract

This study evaluates the effectiveness of satellite-derived tropospheric nitrogen dioxide (NO2) concentrations as a proxy for economic activity in Japan. While nighttime light (NTL) data has been widely used to approximate economic output, recent research has highlighted its' key limitations. In particular, the relationship between NTL and economic outcomes weakens in sub-sample analyses with shorter time spans or restricted geographic coverage. NTL data also faces several key limitations: saturation in dense urban areas reduces measurement accuracy, capturing nighttime emissions fails to account for essential daytime economic activity, inconsistent sensors across different satellites introduce measurement variability, and the technology's sensitivity diminishes when differentiating economic development beyond certain brightness thresholds. Our results show that NO2's effectiveness as an economic proxy is highly dependent on spatial resolution. Using $0.25^\circ \times 0.25^\circ$ resolution NO2 data, we find statistically significant relationships with prefecture-level GDP across multiple sectors. Mining shows the strongest elasticity (3.02%), followed by electricity, gas, and water (1.51%), and manufacturing (0.48%). Agriculture, forestry, and fisheries exhibit negative associations (-0.11%), consistent with vegetation serving as NO2 sinks. However, when using higher resolution $0.1^\circ \times 0.1^\circ$ NO2 data, these relationships largely disappear, with most coefficients becoming statistically insignificant and sometimes counterintuitive. These findings highlight the importance of matching satellite data resolution to the geographic scale of economic analysis, with coarser resolution being optimal for prefecture-level analysis in Japanese context. This research demonstrates NO2's potential as a more reliable alternative to NTL for economic monitoring when appropriately calibrated.

1 Introduction

Accurately measuring economic activity in a timely and geographically precise way attracts the attention of both policymakers and economists. To develop effective actions, policymakers require timely insights into economic situations across different geographic locations, as demonstrated by the COVID-19 pandemic. Traditional indicators, like GDP, have significant limitations for area-specific or near real-time analysis because they usually provide data at the national level with low temporal frequency.

To overcome these limitations, researchers began using alternative satellite-derived indicators that can serve as proxies for economic activity. One common indicator used in economic studies is night-time light (NTL) data, often used in regions with limited data availability or unreliable official statistics.

Henderson et al. (2012) introduced a framework to estimate real GDP growth using NTL data by correlating night-time luminosity data with conventional economic indicators. Using panel data from 188 countries from 1992 to 2008, they show that measured GDP growth correlates with growth in night lights at an elasticity of approximately 0.3, thus a 1% increase in night lights is associated, on average, with a 0.3% increase in measured GDP.

Nevertheless, several recent studies have pointed out key limitations of using night-time light data in economic context. Chen and Nordhaus (2011) show that while NTL data can be useful for estimating output in low-quality statistical environments, its effectiveness decreases in contexts with high-quality data. Mellander et al. (2015) highlight problems with sensor calibration between different satellites, which creates inconsistencies when comparing data across periods. Jean et al. (2016) point out significant saturation problems with NTL data in urban areas, where the sensors cannot distinguish between different levels of economic development once a certain brightness level is reached. Gibson et al. (2021) show that while night light data is widely used, it can be misleading in low-density rural areas, which could lead to underestimation of spatial inequality and misinterpretation of economic conditions.

One possible alternative index to NTL for monitoring economic activities is to use carbon dioxide (CO2), which is emitted when fossil fuel is consumed. However, since the half-life of CO2 is more than 400 years, the present CO2 level is the accumulated result of past economic activity. Given the noise level of measuring CO2 level, it is difficult to measure CO2 emission with reasonable precision. Another alternative is to use nitrogen dioxide (NO2). NO2 emissions result primarily from fossil fuel combustion associated with key economic sectors such as industrial production, transportation, and energy. Unlike CO2, which lingers in the atmosphere, NO2 has a comparatively short atmospheric lifetime (up to 6 hours) and it does not travel very far from its source. Therefore, the locations of NO2 concentrations can be directly determined from the satellite data. Because of these characteristic, NO2 can be used as a sensitive indicator for tracking changes in economic production, making it useful for monitoring shifts in the economy.

Recently, Ezran et al. (2023) shows that satellite-derived NO2 measurements outperform traditional NTL data in capturing economic fluctuations at the national level. They identify several key advantages: NO2 measurements are collected during daytime, when economic activity typically peaks and they are less vulnerable to uncontrollable factors such as atmospheric visibility conditions, conflict-related disruptions, or data manipulation. However, this analysis is limited to national-level comparisons, which overlooks the critical subnational relationship between NO2 and economic activity. Additionally, their research lacks sectoral analysis of NO2 intensity variations across different economic activities.

Therefore, in this study, we analyze the correlation between satellite NO2 data and subnational economic activity across Japanese prefectures, sectors, and cities from 2005 to 2018, using multiple spatial resolutions.

We selected Japan as our study location for several reasons. First, Japan's democratic governance structure ensures reliable economic data, which is crucial given the documented issues with economic reporting in authoritarian regimes.Magee and Doces (2015) show that authoritarian regimes have few limitations and can exaggerate economic growth figures compared to democratic countries. This results in GDP growth rates being overstated by 0.5 to 1.5 percentage points in statistics reported to international agencies like the World Bank. Martinez (2022) prove that by using satellite-based night-time lights as an independent proxy for economic activity and showing that autocracies overstate yearly GDP growth by approximately 35Japan is a democracy, which is believed to maintain accurate economic reporting due to greater transparency and institutional checks. According to the World Bank (2025) Worldwide Governance Indicators, Japan maintains strong performance across multiple dimensions of institutional quality, ranking in the top 80th to 90th percentile for Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption from 2013 to 2023 positioning Japan among the world's most well-governed democracies. This reinforces Japan's suitability as a study location where official economic statistics can be trusted as accurate reflections of actual economic conditions. Furthermore, Japan's performance in the Corruption Perceptions Index (CPI) by Transparency International (2025) further supports its institutional reliability for economic research. Japan scored 71 out of 100 in 2024, ranking 20th globally out of 180 countries. This consistent performance in one of the most widely used corruption rankings indicates low levels of public sector corruption and supports the credibility of Japan's official economic statistics.

Second, Japanese government offers exceptional data availability across multiple spatial and sectoral dimensions. Along with national-level GDP statistics, Japan provides GDP data at the prefectural level as well as sectoral GDP data by prefecture. The availability of such high-resolution NO2 satellite data further enhances our analytical capabilities, enabling detailed subnational analysis that can capture localized economic patterns and variations at the regional level.

Thus, we make several key contributions that extend beyond existing research. First, while previous studies have mostly focused on national-level economic analysis, our research provides a comprehensive subnational analysis. Second, we conduct sectoral analysis across different economic activities to understand how NO2 emissions correlate with specific types of economic output. Third, we use both $0.25° \times 0.25°$ and $0.1° \times 0.1°$ NO2 data from multiple satellite missions including OMI and TROPOMI, which enables us to conduct analysis across different spatial scales and identify which resolution data provides the best detection of prefecture-level economic analysis.

Fourth, we address the challenges of measuring economic activity in the Japanese context, where traditional night-time light data suffers from severe limitations.

These contributions are particularly important given the ongoing discussion about the reliability and universal applicability of satellite-based economic indicators.

2 Materials and Methods

In this study, we use remote sensing data from the Ozone Monitoring Instrument (OMI), which operates in a sun-synchronous polar orbit. It passes over the same location at approximately the same time each day. This ensures consistent observational conditions, which enhances the temporal reliability of our analysis. In the context of Japan, OMI provides daily observations between 13:30 and 14:30 local time. This time frame is advantageous because it coincides with peak economic activity, capturing key industrial operations.

For $0.25° \times 0.25°$ NO2 data we use the Level 3 OMNO2d dataset, which provides daily measurements of NO2. The dataset includes both total and tropospheric vertical column amount of NO2, with and without cloud screening (excludes measurements with cloud fractions greater than 30%) in units of molecules per square centimeter (molec/cm^2)). The observations are aggregated into a global $0.25° \times 0.25°$ degree grid (approximately $27.75\,\mathrm{km} \times 27.75\,\mathrm{km}$ at the equator). The dataset is publicly available via NASA's Goddard Earth Sciences Data and Information Services Center (GES-DISC) Krotkov et al. (2017) and contains data from October 2004 till the present time.

For $0.1° \times 0.1°$ NO2 data, we use the OMNO2d HR product by Lamsal (2021) a high-resolution version of the standard OMNO2d dataset. The dataset includes tropospheric vertical column amounts of NO2, in units of molecules per square centimeter (molec/cm^2)). This dataset retains the same daily coverage and retrieval methodology as OMNO2d but is processed at a $0.1° \times 0.1°$ resolution (approximately $11\,\mathrm{km} \times 11\,\mathrm{km}$ at the equator) with monthly files.

For $0.1° \times 0.1°$ ground-level NO2 data, we utilize high-resolution ground-level concentration estimates derived from multiple satellite-based products developed by Cooper (2022). The primary dataset provides using annual mean estimates for 2005-2019 ground-level nitrogen dioxide concentrations at approximately 1 km spatial resolution, combining TROPOMI satellite and OMI satellite NO2 column observations with information from the GEOS-Chem chemical transport model and ground-based monitoring networks. NO2 concentrations are provided in units of parts per billion by volume (ppbv).

For additional analysis we use $0.1^\circ \times 0.1^\circ$ NO2 data, derived from TROPOMI satellite, computed by Goldberg (2024). It provides annual averages of tropospheric NO2 vertical column density from the Level 3 Tropospheric Monitoring Instrument (TROPOMI) using a consistent algorithm from the European Space Agency (ESA) in units of molecules per square centimeter (molec/cm^2). The TROPOMI instrument on Sentinel-5 Precursor acquires measurements from low Earth orbit (824 km above ground level) once per day globally at approximately 13:30 local time. This dataset was developed by the George Washington University Air, Climate and Health Laboratory as part of the NASA Health Air Quality Applied Science Team (HAQAST) and is publicly available via NASA's Goddard Earth Sciences Data and Information Services Center (GES-DISC).

For NTL data we use the DMSP Nighttime Lights Extension dataset by Ghosh et al. (2021), which provides annual nighttime light intensity measurements derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS). For both NTL levels and NO2 levels we use R to extract values across several specifications.

For both NTL levels and NO2 levels we use R to extract values across several specifications.

For GDP we use Japanese statistical GDP datasets for prefectural-level GDP and prefectural-level sectoral GDP accessed via Statistics Bureau, Ministry of Internal Affairs and Communications (2025). To assess the relationship between satellite-derived NO2 concentrations and various GDP specifications, we use a fixed-effects panel regression framework.

For additional analysis, we compute yearly data from Yamazawa (2022) based on monthly prefecture-level data for all 47 Japanese prefectures. The data uses a production approach.

Our baseline econometric specification is:

$$\ln(\text{GDP}_{it}) = \beta_0 + \beta_1 \ln(\text{NO2}_{it}) + \alpha_i + \gamma_t + \varepsilon_{it} \tag{1}$$

In the above equation, $\ln(\text{GDP}_{it})$ is the natural logarithm of GDP for spatial unit i at time t. $\ln(\text{NO2}_{it})$ is the natural logarithm of NO2 concentration for spatial unit i at time t. α_i and

γ_t capture unit-specific fixed effects and time-fixed effects. ε_{it} is the error term. This specification helps us examine whether variations in NO2 concentrations meaningfully explain variations in economic activity across both spatial units and time periods. The coefficient β_1 indicates the expected change in GDP associated with a one-unit increase in NO2 concentration, holding all other factors constant. This natural log-log specification is particularly advantageous for several reasons. On one hand, logarithmic transformation helps stabilize the variance across observations of both dependent and independent variables. On the other hand, it allows for interpreting β_1 as an elasticity. Thus, a percentage change in GDP is associated with a one percent change in NO2.

3 Results

3.1 Prefecture-level estimations using satellite NO2 measurements at $0.25° \times 0.25°$ resolution

Table 1 shows the baseline summary statistics for the main variables used in the analysis, which include a combination of economic and satellite-based indicators.

Table 1. Summary Statistics

Variable	Mean	SD	Min	Max
	(1)	(2)	(3)	(4)
Year	2011.5	4.034	2005	2018
Prefecture Code	24	13.575	1	47
Ln of Gross Prefectural Product in trill. yen	1.967	0.844	0.548	4.673
Ln of Prefectural GDP in agriculture, forestry and fisheries industry in trill. yen	-2.399	0.666	-3.929	-0.139
Ln of Prefectural GDP in construction industry in trill. yen	-0.898	0.760	-2.279	1.582
Ln of Prefectural GDP in electricity, gas and water industry in trill. yen	-1.584	0.800	-3.142	0.477
Ln of Prefectural GDP in manufacturing industry in trill. yen	0.349	0.973	-1.884	2.764
Ln of Prefectural GDP in mining industry in trill. yen	-5.107	0.946	-8.217	-2.267
Ln of NTL	2.482	0.639	1.156	3.957
Trop. NO2 (10^15 molec/cm2, resolution: 0.25x0.25)	1.596	0.750	0.475	4.734
Ln of Trop. NO2 (10^15 molec/cm2, resolution: 0.25x0.25)	0.366	0.450	-0.744	1.555
Weighted Trop. NO2 (10^15 molec/cm2, resolution: 0.25x0.25)	1.597	0.755	0.469	4.689
Ln of Weighted Trop. NO2 (10^15 molec/cm2, resolution: 0.25x0.25)	0.364	0.455	-0.756	1.545
Trop. NO2 (10^15 molec/cm2, resolution: 0.1x0.1)	4.278	2.660	0.781	15.084
Ln of Trop. NO2 (10^15 molec/cm2, resolution: 0.1x0.1)	1.273	0.611	-0.247	2.714
Observations		658		
Ground-level NO2 (ppb, resolution: 0.1x0.1)	0.230	0.132	0.077	0.884
Ln of Ground-level NO2 (ppb, resolution: 0.1x0.1)	-1.581	0.442	-2.568	-0.124
Observations		644		

Table 2 shows fixed effects panel regression results analyzing the relationship between satellite-derived NTL and NO2 measures and prefecture-level GDP generated by Japan. The table also compares the effectiveness of two primary satellite-derived proxies: NTL and tropospheric NO2 concentrations as economic proxies.

Table 2. Assosiation between NO2 and Prefecture Level GDP: Using 0.25x0.25 Degree Spatial Resolution NO2 data

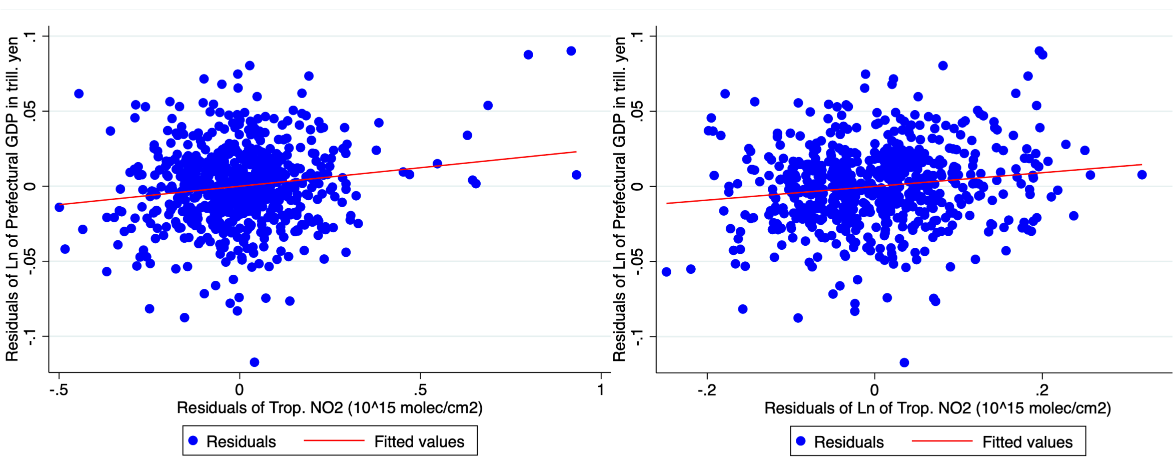
Dependant Variable	Ln of Prefectural GDP in trill. yen				
Estimation Model	Fixed Effects Panel Regression				
Variables	(1)	(2)	(3)	(4)	(5)
Ln of NTL	0.03257				
	(0.026)				
Trop. NO2 (10^15 molec/cm2)		0.02465*			
		(0.013)			
Ln of Trop. NO2 (10^15 molec/cm2)			0.04560*		
			(0.023)		
Weighted Trop. NO2 (10^15 molec/cm2)				0.02385*	
				(0.014)	
Ln of Weighted Trop. NO2 (10^15 molec/cm2)					0.04401*
					(0.024)
Number of prefectures	47	47	47	47	47
Observations	658	658	658	658	658
R-squared	0.999	0.999	0.999	0.999	0.999
Partial R-squared	0.0142	0.0237	0.0225	0.0212	0.0195
Control Variables					
Prefecture Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes

Notes: NO2 specification uses 0.25x0.25 spatial resolution. Weighted Trop. NO2 represents measurements weighted by data quality metrics. Clustered robust standard errors are in parentheses, assuming error terms are correlated within each prefecture over time. *** p<0.01, ** p<0.05, * p<0.1

Column (1) shows that the natural logarithm of NTL has a positive but statistically insignificant coefficient (0.03257), reaffirming existing concerns regarding night-time light data's limited sensitivity in high-income regions where economic activity may saturate detectable luminosity levels. Column (2) shows that tropospheric NO2 has a positive and statistically significant relationship with prefectural GDP. The coefficient of 0.02465 is significant at the 10% level. Column (3) shows the results using the natural logarithm of tropospheric NO2, which also shows a positive and statistically significant coefficient of 0.04560 at the 10% level. Thus, a 1% increase in tropospheric NO2 correlates with an approximate 0.046% increase in prefectural GDP. Column (4) shows a weighted tropospheric NO2 coefficient of 0.02385, also statistically significant at the 10% level. Column (5) shows the result using the natural logarithm of weighted tropospheric NO2, which also shows a positive and statistically significant coefficient of 0.04041 at the 10% level. Thus, a 1% increase in quality-weighted NO2 correlates with an approximate 0.040% increase in GDP.

To analyze the causal relationship between NO2 and GDP, we use the Frisch-Waugh-Lovell (FWL) theorem to control for unseed characteristics. This helps us isolate the true correlation between satellite-derived NO2 measurements and economic activity.

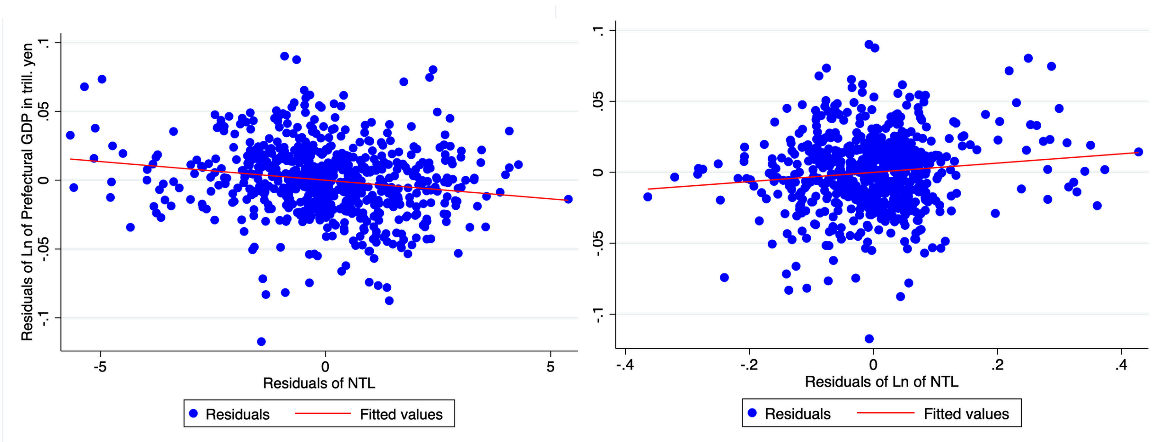
Figure 1. Residual correlation between tropospheric NO2 and GDP
after controlling for prefecture and year fixed effects



Notes: Each plot shows the relationship between residuals derived from two separate regressions: one regressing natural logarithm of Prefectural GDP on prefecture and year fixed effects, and another regressing NO2 measurements on identical fixed effects. The left panel uses scaled NO2 values, while the right panel uses natural logarithm transformations.

Figure 1 shows the graphical relationship between X and Y after controlling the prefecture fixed effect and time fixed effect. We visualize the relationship between GDP and NO2 after removing all variation attributable to prefecture-specific characteristics and year-specific trends. The slight positive slopes of the fitted red lines confirm a positive association between NO2 emissions and economic activity. The coefficient from these residual regressions is identical to what we obtain in our full fixed-effects panel regression models.

Figure 2. Residual correlation between NTL and GDP
after controlling for prefecture and year fixed effects



Notes: The plot shows the relationship between residuals derived from two separate regressions: one regressing natural logarithm of Prefectural GDP on prefecture and year fixed effects, and another regressing natural logarithm of nighttime lights (NTL) on identical fixed effects.

Figure 2 shows the relationship between nighttime lights (NTL) and GDP after controlling for prefecture and year fixed effects through residual analysis. The left panel displays the relationship using NTL in levels, while the right panel shows the relationship using the natural logarithm of NTL. The left panel reveals a negative association between residualized NTL levels and residualized log GDP, as indicated by the downward-sloping red fitted line. The scattered distribution of observations spans a wide range across the horizontal axis, with considerable dispersion in the relationship. The right panel shows a positive association between residualized log NTL and residualized log GDP, with the upward-sloping red fitted line confirming a positive relationship between these variables.

The critical distinction is that NO2 maintains a consistent positive relationship with GDP in both specifications, while NTL exhibits opposite signs depending on the transformation used. Thus, NO2 shows robust consistency across both specifications, suggesting that the underlying NO2-GDP relationship is stable and linear-like in nature. This consistency indicates that NO2 may have a more straightforward proportional relationship with economic activity, where both absolute and percentage changes yield similar directional effects.

After identifying the overall link between satellite data and economic activity at the prefecture level, we extended our analysis to different economic sectors. This sectoral approach helps us see which industries are best tracked using satellite indicators and whether NO2 or NTL data are more effective for certain activities.

Table 3 shows fixed effects panel regression results analyzing the relationship between satellite-derived NTL and NO2 measures and prefecture-level GDP generated by Japan's mining sector.

Table 3. Assosiation between NO2 and Prefecture Level GDP in mining sector: Using 0.25x0.25 Degree Spatial Resolution NO2 data

Dependant Variable	Ln of Prefectural GDP in mining sector in trill. yen				
Estimation Model	Fixed Effects Panel Regression				
Variables	(1)	(2)	(3)	(4)	(5)
Ln of NTL	0.52093**				
	(0.219)				
Trop. NO2 (10^15 molec/cm2)		0.30893***			
		(0.092)			
Ln of Trop. NO2 (10^15 molec/cm2)			0.61428***		
			(0.190)		
Weighted Trop. NO2 (10^15 molec/cm2)				0.31626***	
				(0.096)	
Ln of Weighted Trop. NO2 (10^15 molec/cm2)					0.63762***
					(0.203)
Number of prefectures	47	47	47	47	47
Observations	658	658	658	658	658
R-squared	0.931	0.931	0.932	0.931	0.932
Partial R-squared	0.0390	0.0400	0.0439	0.0400	0.0440
Control Variables					
Prefecture Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes

Notes: NO2 specification uses 0.25x0.25 spatial resolution. Weighted Trop. NO2 represents measurements weighted by data quality metrics. Clustered robust standard errors are in parentheses, assuming error terms are correlated within each prefecture over time. *** p<0.01, ** p<0.05, * p<0.1

Column (1) shows that the natural logarithm of NTL has a positive and statistically significant coefficient (0.52093), significant at the 5% level. This suggests that, NTL may still serve as a relevant proxy for mining activity. Column (2) shows that tropospheric NO2 has a positive and statistically significant relationship with prefectural mining GDP. The coefficient of 0.30893 is significant at the 1% level. Column (3) shows the results using the natural logarithm of tropospheric NO2, which also shows a positive and statistically significant coefficient of 0.61422 at the 1% level. Thus, a 1% increase in tropospheric NO2 correlates with an approximate 0.614% increase in prefectural mining GDP. Column (4) shows a weighted tropospheric NO2 coefficient of 0.31626, also statistically significant at the 1% level. Column (5) shows the result using the natural logarithm of weighted tropospheric NO2, which also shows a positive and statistically significant coefficient of 0.63762 at the 1% level. Thus, a 1% increase in quality-weighted NO2 correlates with an approximate 0.638% increase in mining GDP.

The results in Table 3 shows a consistent and statistically significant relationship between tropospheric NO2 concentrations and mining sector GDP across all model specifications. These results suggest that satellite indicators are particularly effective at tracking mining sector activity, with both NTL and NO2 measures showing robust statistical relationships, NO2 measurements demonstrate stronger correlations and higher statistical significance. Despite the significance of NTL in the mining sector, NO2 remains a more robust proxy because it directly captures emissions from fuel combustion and industrial processes, which are closely tied to mining activity. This makes NO2 particularly valuable for near real-time monitoring of mining production fluctuations, while still maintaining the convenience of frequent and global coverage.

Table 4 shows fixed effects panel regression results analyzing the relationship between satellite-derived NTL and NO2 measures and prefecture-level GDP generated by Japan's electricity, gas, and water utility sector.

Table 4. Assosiation between NO2 and Prefecture Level GDP in electricity, gas and water sector:
Using 0.25x0.25 Degree Spatial Resolution NO2 data

Dependant Variable	Ln of Prefectural GDP in electricity, gas and water sector in trill. yen				
Estimation Model	Fixed Effects Panel Regression				
Variables	(1)	(2)	(3)	(4)	(5)
Ln of NTL	0.25622**				
	(0.126)				
Trop. NO2 (10^15 molec/cm2)		0.10579*			
		(0.053)			
Ln of Trop. NO2 (10^15 molec/cm2)			0.25636**		
			(0.123)		
Weighted Trop. NO2 (10^15 molec/cm2)				0.10651*	
				(0.057)	
Ln of Weighted Trop. NO2 (10^15 molec/cm2)					0.24456*
					(0.132)
Number of prefectures	47	47	47	47	47
Observations	658	658	658	658	658
R-squared	0.965	0.965	0.965	0.965	0.965
Partial R-squared	0.0263	0.0131	0.0213	0.0127	0.0180
Control Variables					
Prefecture Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes

Notes: NO2 specification uses 0.25x0.25 spatial resolution. Weighted Trop. NO2 represents measurements weighted by data quality metrics. Clustered robust standard errors are in parentheses, assuming error terms are correlated within each prefecture over time. *** p<0.01, ** p<0.05, * p<0.1

Column (1) shows that the natural logarithm of NTL has a positive and statistically significant coefficient (0.25622), significant at the 5% level, meaning that NTL effectively captures electricity, gas, and water sector activity, likely due to their close association with infrastructure and energy use. Column (2) shows that tropospheric NO2 has a positive and statistically significant relationship with GDP in the electricity, gas, and water sector. The coefficient of 0.10579 is significant at the 10% level. Column (3) shows the results using the natural logarithm of tropospheric NO2, which also shows a positive and statistically significant coefficient of 0.25636 at the 5% level. Thus, a 1% increase in tropospheric NO2 correlates with an approximate 0.256% increase in sectoral GDP. Column (4) shows a weighted tropospheric

NO2 coefficient of 0.10651, statistically significant at the 10% level. Column (5) shows the result using the natural logarithm of weighted tropospheric NO2, which also shows a positive and statistically significant coefficient of 0.24456 at the 10% level. Thus, a 1% increase in quality-weighted NO2 correlates with an approximate 0.245% increase in electricity, gas, and water GDP.

The results in Table 4 indicate that both night-time lights and tropospheric NO2 are useful proxies for estimating economic activity in the electricity, gas, and water sector. While the coefficient on NTL is statistically significant and positive, suggesting some relevance of luminosity in this infrastructure-intensive sector, the NO2 indicators consistently exhibit stronger statistical significance and larger partial R-squared values across all specifications. Thermal power plants, which dominate Japan's electricity sector, directly emit substantial NOx during combustion processes, creating a direct physical relationship between electricity production and atmospheric NO2 concentrations. The higher coefficients for NO2 measurements compared to NTL indicate greater sensitivity to production changes.

Table 5 shows fixed effects panel regression results analyzing the relationship between satellite-derived NTL and NO2 measures and prefecture-level GDP generated by Japan's agriculture, forestry, and fisheries sector.

Table 5. Assosiation between NO2 and Prefecture Level GDP in agriculture, forestry and fisheries sector:
Using 0.25x0.25 Degree Spatial Resolution NO2 data

Dependant Variable	Ln of Prefectural GDP in agriculture, forestry and fisheries sector in trill. yen				
Estimation Model	Fixed Effects Panel Regression				
Variables	(1)	(2)	(3)	(4)	(5)
Ln of NTL	-0.10612				
	(0.133)				
Trop. NO2 (10^15 molec/cm2)		-0.04544*			
		(0.025)			
Ln of Trop. NO2 (10^15 molec/cm2)			-0.09149		
			(0.060)		
Weighted Trop. NO2 (10^15 molec/cm2)				-0.04692*	
				(0.024)	
Ln of Weighted Trop. NO2 (10^15 molec/cm2)					-0.09773*
					(0.058)
Number of prefectures	47	47	47	47	47
Observations	658	658	658	658	658
R-squared	0.988	0.988	0.988	0.988	0.988
Partial R-squared	0.0186	0.00993	0.0112	0.0101	0.0118
Control Variables					
Prefecture Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes

Notes: NO2 specification uses 0.25x0.25 spatial resolution. Weighted Trop. NO2 represents measurements weighted by data quality metrics. Clustered robust standard errors are in parentheses, assuming error terms are correlated within each prefecture over time. *** p<0.01, ** p<0.05, * p<0.1

Column (1) shows that the natural logarithm of NTL has a negative but statistically insignificant coefficient (–0.10612), suggesting that NTL data is poorly suited to capture activity in the agriculture, forestry, and fisheries sector, likely due to its rural and low-luminosity characteristics. Column (2) shows that tropospheric NO2 has a negative and statistically significant relationship with sectoral GDP. The coefficient of –0.04514 is significant at the 10% level. Column (3) shows the results using the natural logarithm of tropospheric NO2, which remains negative (–0.09149) but statistically insignificant, indicating a weaker and less precise relationship. Column (4) shows a weighted tropospheric NO2 coefficient of –0.04692, statistically significant at the 10% level, reinforcing the inverse relationship between pollution and agricultural sector output. Column (5) shows the result using the natural logarithm of weighted tropospheric NO2, with a negative and statistically significant coefficient of –0.09773 at the 10% level. This implies that a 1% increase in NO2 is associated with approximately a 0.098% decline in agricultural GDP.

One reason why the values for this sector could be negative is because forests play a crucial role in mitigating air pollution by acting as natural sinks of NO2. Through a process known as dry deposition, forests absorb NO2 directly onto leaf surfaces, where it can either be stored, transformed, or absorbed into plant tissues. For instance, Nowak et al. (2006) estimate that trees in the United States removed approximately 846,000 tons of air pollutants in 1994, including significant quantities of NO2, thereby providing both environmental and economic benefits. This pollution removal mechanism helps explain the seed negative association between NO2 levels and GDP from the agriculture, forestry, and fisheries sector: forested areas may exhibit lower NO2 concentrations, which could correspond with lower measured economic activity.

Table 6 shows fixed effects panel regression results analyzing the relationship between satellite-derived NTL and NO2 measures and prefecture-level GDP generated by Japan's construction industry.

Table 6. Assosiation between NO2 and Prefecture Level GDP in construction sector: Using 0.25x0.25 Degree Spatial Resolution NO2 data

Dependant Variable	Ln of Prefectural GDP in construction sector in trill. yen				
Estimation Model	Fixed Effects Panel Regression				
Variables	(1)	(2)	(3)	(4)	(5)
Ln of NTL	0.03571				
	(0.081)				
Trop. NO2 (10^15 molec/cm2)		0.06153*			
		(0.035)			
Ln of Trop. NO2 (10^15 molec/cm2)			0.13308		
			(0.090)		
Weighted Trop. NO2 (10^15 molec/cm2)				0.06572*	
				(0.037)	
Ln of Weighted Trop. NO2 (10^15 molec/cm2)					0.13863
					(0.097)
Number of prefectures	47	47	47	47	47
Observations	658	658	658	658	658
R-squared	0.977	0.977	0.977	0.977	0.977
Partial R-squared	0.000879	0.00761	0.00987	0.00828	0.00995
Control Variables					
Prefecture Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes

Notes: NO2 specification uses 0.25x0.25 spatial resolution. Weighted Trop. NO2 represents measurements weighted by data quality metrics. Clustered robust standard errors are in parentheses, assuming error terms are correlated within each prefecture over time. *** p<0.01, ** p<0.05, * p<0.1

Column (1) shows that the natural logarithm of NTL has a positive but statistically insignificant coefficient (0.03571), indicating limited explanatory power. Column (2) shows that tropospheric NO2 has a positive and statistically significant relationship with construction GDP. The coefficient of 0.06153 is significant at the 10% level. Column (3) shows results using the natural logarithm of tropospheric NO2, which yields a positive but statistically insignificant coefficient of 0.13308. Column (4) shows a weighted tropospheric NO2 coefficient of 0.06572, significant at the 5% level, reinforcing the link between NO2 concentrations and construction activity when accounting for data quality. Column (5) shows the result using the natural logarithm of weighted tropospheric NO2, producing a positive but statistically insignificant coefficient of 0.13863. The results suggest a modest positive association between NO2 and construction sector GDP, with significance detected particularly in regular NO2 specifications.

Table 7 shows fixed effects panel regression results analyzing the relationship between satellite-derived NTL and NO2 measures and prefecture-level GDP generated by Japan's manufacturing sector.

Table 7. Assosiation between NO2 and Prefecture Level GDP in manufacturing sector: Using 0.25x0.25 Degree Spatial Resolution NO2 data

Dependant Variable	Ln of Prefectural GDP in manufacturing sector in trill. yen				
Estimation Model	Fixed Effects Panel Regression				
Variables	(1)	(2)	(3)	(4)	(5)
Ln of NTL	-0.06681				
	(0.045)				
Trop. NO2 (10^15 molec/cm2)		0.06164			
		(0.057)			
Ln of Trop. NO2 (10^15 molec/cm2)			0.05796		
			(0.081)		
Weighted Trop. NO2 (10^15 molec/cm2)				0.05403	
				(0.061)	
Ln of Weighted Trop. NO2 (10^15 molec/cm2)					0.04511
					(0.084)
Number of prefectures	47	47	47	47	47
Observations	658	658	658	658	658
R-squared	0.993	0.993	0.993	0.993	0.993
Partial R-squared	0.00646	0.0160	0.00393	0.0118	0.00221
Control Variables					
Prefecture Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes

Notes: NO2 specification uses 0.25x0.25 spatial resolution. Weighted Trop. NO2 represents measurements weighted by data quality metrics. Clustered robust standard errors are in parentheses, assuming error terms are correlated within each prefecture over time. *** p<0.01, ** p<0.05, * p<0.1

Column (1) shows that the natural logarithm of NTL has a negative but statistically insignificant coefficient (–0.06681). Column (2) shows that tropospheric NO2 has a positive coefficient of 0.06164, indicating a direct relationship between NO2 emissions and manufacturing GDP. Column (3) shows the result using the natural logarithm of tropospheric NO2, with a coefficient of 0.05796. Thus, a 1% increase in NO2 is associated with a 0.058% increase in manufacturing GDP. Column (4) shows a weighted tropospheric NO2 a positive coefficient of 0.05403. Column (5) shows the result using the natural logarithm of weighted tropospheric NO2 with positive coefficient of 0.04511. This suggests that a 1% increase in quality-weighted NO2 corresponds to a 0.045% increase in manufacturing GDP.

The results in Table 7 consistently show positive coefficients across all NO2 specifications, suggesting a meaningful directional link between NO2 emissions and manufacturing sector output. Despite the lack of statistical significance, the magnitude and coherence of the coefficients—ranging from 0.045 to 0.062—support the interpretation that NO2 remains a relevant proxy for tracking industrial activity in emissions-heavy sectors like manufacturing.

Our sectoral analysis demonstrates that satellite indicators perform differently across different sectors. NO2 measurements show particularly strong relationships with mining and utility sectors, construction and manufacturing, where production directly generates emissions. However, in the agriculture, forestry, and fisheries sector, we see negative relationships, reflecting these sectors' role as pollution sinks.

3.2 Does the Use of A Higher Resolution Data generate better results? Analysis using $0.1^\circ \times 0.1^\circ$ spational resolution NO2 data

Table 8 shows fixed effects panel regression results analyzing the relationship between satellite-derived NO2 measures and prefecture-level GDP generated by Japan.

Table 8. Assosiation between NO2 and Prefecture Level GDP:
Using 0.1x0.1 Degree Spatial Resolution NO2 data

Dependant Variable	Ln of Prefectural GDP in trill. yen			
Estimation Model	Fixed Effects Panel Regression			
Variables	(1)	(2)	(3)	(4)
Trop. NO2 (10^15 molec/cm2)	-0.00830**			
	(0.004)			
Ln of Trop. NO2 (10^15 molec/cm2)		-0.03836		
		(0.034)		
Ground-level NO2 (ppb)			0.00669	
			(0.028)	
Ln of Ground-level NO2 (ppb)				-0.00360
				(0.012)
Number of prefectures	47	47	46	46
Observations	658	658	644	644
R-squared	0.999	0.999	0.999	0.999
Partial R-squared	0.0283	0.0117	0.000156	0.000241
Control Variables				
Prefecture Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes

Notes: NO2 specification uses 0.1x0.1 spatial resolution. High-resolution ground-level concentration estimates do not have information on NO2 of Okinawa prefecture, thus the number of prefectures in Column (3) and Column (4) is 46. High-resolution ground-level NO2 concentrations are provided in units of parts per billion by volume (ppbv). Clustered robust standard errors are in parentheses, assuming error terms are correlated within each prefecture over time. *** p<0.01, ** p<0.05, * p<0.1

Column (1) shows a contrasting result where tropospheric NO2 exhibits a negative and statistically significant relationship with prefectural GDP. The coefficient of -0.00830 is significant at the 1% level, suggesting an inverse relationship between satellite-derived 0.1 degree by 0.1 NO2 concentrations and economic output. Column (2) shows the natural logarithm of tropospheric NO2 with a negative but statistically insignificant coefficient of -0.03836. Column (3) shows ground-level NO2 measurements with a positive but statistically insignificant coefficient of 0.00669. This suggests that surface-level NO2 concentrations may capture different economic dynamics compared to tropospheric measurements. Column (4) shows the natural logarithm of ground-level NO2, which produces a negative and statistically insignificant coefficient of -0.00360.

These results demonstrate that the higher spatial resolution ($0.1° \times 0.1°$) NO2 measurements perform substantially worse at capturing prefecture-level economic activity compared to the standard $0.25° \times 0.25°$ resolution used in our baseline analysis.

Table 9 shows fixed effects panel regression results analyzing the relationship between satellite-derived TROPOMI NO2 measures and prefecture-level GDP generated by Japan.

Table 9. Assosiation between NO2 and Prefecture Level GDP: Using 0.1x0.1 Degree Spatial Resolution TROPOMI NO2 data

Dependant Variable	Ln of Gross Prefectural Product in trill.yen	
Extimation Model	Fixed Effect Panel Regression	
Variables	(1)	(2)
Trop. NO2 (10^15 molecules/cm2)	-0.00734	
	(0.006)	
Ln of Trop. NO2 (10^15 molecules/cm2)		-0.03475
		(0.025)
Number of Prefectures	47	47
Observations	282	282
R-squared	1.000	1.000
Partial R-squared	0.00645	0.0102
Control variables		
Prefecture fixed effect	Yes	Yes
Year fixed effect	Yes	Yes

Notes: NO2 specification uses 0.1x0.1 spatial resolution. Clustered robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Column (1) shows that tropospheric NO2 has a negative coefficient (-0.00734), which is statistically insignificant. Column (2) shows the results using the natural logarithm of tropospheric NO2, which yields a negative and statistically insignificant coefficient of -0.03475. The negative coefficients in both specifications suggest that the higher spatial resolution TROPOMI data leads to unexpected negative relationship suggesting that at higher spatial resolutions, the relationship between NO2 emissions and economic activity is not consistent with theoretical expectations.

Thus, while NO2 may serve as an economic proxy at coarser spatial resolutions, the relationship becomes less reliable and potentially counterintuitive when using finer spatial resolution data.

4 Discussion

This research demonstrates that tropospheric nitrogen dioxide (NO2) concentrations derived from satellite observations serve as an effective proxy for economic activity in Japan. This research demonstrates that tropospheric nitrogen dioxide (NO2) concentrations derived from satellite observations serve as an effective proxy for economic activity in Japan, but the effectiveness is highly dependent on matching spatial resolution to analytical scale. Our analysis reveals a clear resolution-scale dependency that has important implications for satellite-based economic monitoring.

The most significant finding of this study is the systematic difference in NO2 performance across spatial resolutions. At $0.25° \times 0.25°$ resolution, NO2 measurements demonstrate robust statistical relationships with prefecture-level economic activity. Mining and utility sectors show particularly significant correlations, with elasticities of 3.02% and 1.51% respectively, reflecting the emission-intensive nature of these industries. The construction industry similarly shows positive correlations (0.48%), while agriculture, forestry, and fisheries exhibit theoretically consistent negative relationships (-0.11%), illustrating these sectors' role as pollution sinks.

However, when the same analysis is conducted using higher resolution $0.1° \times 0.1°$ NO2 data at the prefecture level, these relationships disappear. Most coefficients become statistically insignificant, and some even change signs in counterintuitive ways. This suggests that spatial aggregation at the 0.25 scale may be optimal for capturing prefecture-level economic dynamics.

The limitations of NTL data are clearly evident across our analysis. At the prefecture level, NTL shows consistently weak and statistically insignificant relationships with GDP, supporting theoretical concerns regarding saturation problems in urban areas and NTL's inability to capture daytime economic activities.

Our findings have several important implications. First, we suggest to use such satellite data resolution that is applicable to a particular analytical scale. Our results suggest using 0.25 resolution for prefecture-level and perhaps regional economic analysis. Second, NO2 proves to be particularly valuable for monitoring emission-intensive sectors (mining, utilities, manufacturing) while providing insights into environmental processes (negative correlations with forestry sectors). Third, the significant correlations between NO2 and economic activity, when properly calibrated for scale, offer significant advantages for high-frequency economic monitoring.

Our research shows that spatial resolution is critical for satellite-based economic indicators. As satellite technology improves, researchers need to understand the resolution effects to build effective economic monitoring systems that can provide faster, more detailed economic data than traditional statistics.

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