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Nighttime lights time series of tsunami damage, recovery, and economic metrics in Sumatra, Indonesia

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Abstract

On 26 December 2004, a magnitude 9.2 earthquake off the west coast of the northern Sumatra, Indonesia resulted in 160,000 Indonesians killed. We examine the Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) nighttime light imagery brightness values for 307 communities in the Study of the Tsunami Aftermath and Recovery (STAR), a household survey in Sumatra from 2004 to 2008. We examined night light time series between the annual brightness and extent of damage, economic metrics collected from STAR households and aggregated to the community level. There were significant changes in brightness values from 2004 to 2008 with a significant drop in brightness values in 2005 due to the tsunami and pre-tsunami nighttime light values returning in 2006 for all damage zones. There were significant relationships between the nighttime imagery brightness and per capita expenditures, and spending on energy and on food. Results suggest that Defense Meteorological Satellite Program nighttime light imagery can be used to capture the impacts and recovery from the tsunami and other natural disasters and estimate time series economic metrics at the community level in developing countries.

1. Introduction

On 26 December 2004, there was a magnitude 9.2 earthquake off the west coast of Sumatra, Indonesia. The earthquake resulted in a tsunami that affected fourteen countries around the Indian Ocean. It is estimated that the tsunami killed over 200,000 people and more than 1.5 million people were displaced (Doocy *et al.* 2007). Indonesia was the country most devastated by the tsunami with over 160,000 people thought to have been killed, some 700,000 displaced, and far-reaching damage to the society, economy, and environment that is estimated to be worth over \$4 billion (Doocy *et al.* 2007, Frankenberg *et al.* 2008). The earthquake and tsunami were followed by a massive influx of aid and assistance in excess of \$7 billion, which amounts to the largest reconstruction effort ever mounted in any

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developing country. These aggregate estimates are, at best, rough and quantifying the macro-level impact of the tsunami and the subsequent reconstruction remains a significant challenge.

The Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) provides nighttime light imagery at a global spatial scale. The satellites have a near-polar orbit at an altitude of 830 km and contain visible and infrared sensors that collect nighttime light imagery at 30 arc second (~1 km at the equator) pixel resolution images across a 3000 km swath. Nighttime light imagery has been used to estimate changes in the distribution of the population at a national level (Elvidge *et al.* 1997, Small *et al.* 2005) and to estimate changes in population sizes in neighborhoods (Agnew *et al.* 2008). The evidence suggests that nighttime light imagery has the potential to contribute to quantifying the impact of tsunami damage (Kohiyama *et al.* 2004) as well as the rate of recovery and reconstruction in the years following the tsunami. Nighttime lights also have a high coefficient of determination (i.e. $R^2 > 80\%$) with gross domestic product at a national level and sub-national level (states and cities) in the USA and Europe (Elvidge *et al.* 1997, Doll *et al.* 2006). However, there are few studies that have examined if nightlights can be used to predict the economic activity at the community or household level.

To provide evidence on this issue, nightlight data are compared with extensive household survey data collected in Indonesia before and after the Indian Ocean tsunami. The Study of the Tsunami Aftermath and Recovery (STAR) is a large-scale longitudinal household survey that follows respondents who were living in over 300 communities along the coasts of the provinces of Aceh and North Sumatra, Indonesia before the 2004 Indian Ocean Tsunami. The STAR surveys, which were administered to the same households annually before the tsunami in 2004 and after the tsunami 2005–2008, provide detailed information on the economic and demographic characteristics of the sampled households (Frankenberg *et al.* 2008). These data can be compared with nightlight brightness measures in the same communities to provide insight into the value of nightlight imagery for quantifying metrics associated with economic activity and recovery after a major disaster.

This research has two primary objectives. First, we examine nightlight time series to test the hypothesis that there was a significant decline in nightlight imagery after the tsunami and test the hypothesis that nightlight brightness has recovered to pre-tsunami intensities. Second, we identify relationships with light brightness and economic metrics from 2004 to 2008. This is undertaken to cross-validate the nightlight and economic data and to also improve our understanding of the applications of nighttime light imagery for monitoring damage and recovery after natural hazards.

2. Methods

2.1. Nighttime light imagery

We used nighttime light imagery from the Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS). The system was originally designed to view clouds by moonlight; but the OLS is also used to map the locations of stable lights on the earth's surface (NOAA 2013). The files contain cloud-free composites made using all the

available archived DMSP-OLS smooth resolution data for calendar years. The products are 30 arc second grids, spanning 180° W to 180° E longitude and 65° S to 75N latitude. The imagery is derived from the average visible band digital number or brightness value of cloud-free light detections multiplied by the percent frequency of light detection (NOAA 2013). The inclusion of the percent frequency of detection term normalizes the resulting digital values for variations in the persistence of lighting.

We used the DMSP-OLS F16 satellite, which was launched on 18 October 2003 and began operation on 4 November 2003. The stable night light images from 2004 to 2008 were downloaded from NOAA National Geophysical Data Center (NOAA 2013). We used ENVI 4.8 (Exelis Visual Information Solutions, Boulder) to open nighttime light imagery and extracted the 307 annual STAR points and exported nighttime light digital numbers to ArcGIS (figure 1). The vector shape files included the information from the waves of the Study of the Tsunami Aftermath and Recovery (STAR) in the 307 survey communities. Annual composites from 2004 to 2008 were inter-calibrated using coefficients from Elvidge et al. (2009). We then export all data to ArcGIS version 9.3.1 (ESRI, Redlands) to create new point data layers that included inter-calibrated nighttime light brightness values for all STAR points from 2004 to 2008.

2.2. Extent of tsunami-related damage

We constructed a community-level metric of tsunami-related damage by combining remotely sensed data from the National Aeronautics and Space Administration's Moderate Resolution Imaging Spectroradiometer (MODIS) sensor with survey data. MODIS imagery in the visible and infrared bands at 250 m pixel size from 17 December 2004 and 29 December 2004 were downloaded and geographically linked to each enumeration area included in the STAR survey. Using a 3×3 pixel window over the center of each community, we assessed the degree to which the pre-tsunami ground cover visible in 17 December 2004 image had been replaced by bare earth by 29 December 2004 based on a Normalized Difference Vegetation Index. Each point was then quantified by the number of pixels that changed to bare earth (i.e. 0 to 9 pixels bare earth) (figure 2).

Communities were then stratified into four zones based on the extent of damage. These classifications were cross-validated with information on local area land and infrastructure damage collected at the enumeration area (or community) level as part of the first post-tsunami STAR survey (Frankenberg *et al.* 2008). This classification corresponds well with other evidence gathered independently by our interviewers during their visits to survey communities. There were strong and statistically significant correlations between the remotely sensed measures of damage and community leaders' retrospective reports as well as field supervisors' observations of the degree of damage in each of the survey communities (polychoric correlations were 0.84 and 0.79, respectively) (Frankenberg *et al.* 2008). Heavy damage accounts for 15% of the communities, half of which had eight or nine pixels replaced by bare earth. Moderate damage areas accounts for 17% of the communities and on average, 5.8 pixels were turned to bare earth after the tsunami in these communities. Light damage areas had one or two pixels converted to bare earth; they account for 25% of

the study sites. Communities classified as having no damage had no pixels with bare earth and accounts for 43% of the study sites.

2.3. Economic activity

We use real household per capita expenditure (PCE) which measures the amount people spend (including the imputed value of what they consume out of their own production and from gifts in kind). PCE is a local area analogy to per capita gross domestic product. If there is no saving, it will be the same as per capita income. It is widely regarded as a better measure of resource usage than income for at least two reasons. First, income is notoriously difficult to measure and tends to understate the value of transfers from the public sector, family, and friends. This is important in our study context since there was a massive influx of aid into the tsunami-affected communities and these transfers will be understated or missed altogether in measures of income. Many studies across the globe have established that household PCE is a better indicator of economic resources than household income (Deaton 1997). Second, when earnings are low, people typically draw on savings to maintain their spending above some desirable threshold. Income will miss this behavioral response to the tsunami – a response that consumption is designed to capture.

In each household, the most knowledgeable respondent was administered a consumption and expenditure module that takes, on average, 30 minutes to complete. The respondent is asked about spending in the last week as well as the imputed value of own production and gifts or assistance (for 15 food groups such as rice, meat, vegetables), the last month and 12 months for 12 groups of semi-durables such as clothing, utilities, education, health expenses. To capture variation in prices and changes in prices (inflation), all expenditures are deflated using estimates of local area price indices. Since spending rises with household size, household expenditure is divided by household size to calculate PCE.

2.4. Statistical analysis

A one-way analysis of variance (ANOVA) was used to identify significant differences in nightlight light brightness over a five-year period. STAR data on household expenditures, utility expenditures, and food expenditures were regressed with nightlight bright lights as an indicator variable. Per capita expenditure (PCE) was distributed asymmetrically and we transformed PCE into the logarithm of per capita expenditure, $\ln(\text{PCE})$, the distribution of which is reasonably approximated by a Gaussian distribution. The same was done for utility expenditures and food expenditures. The regressions that relate nightlight brightness to economic activity were estimated separately year by year. We undertook analysis excluding all zero nightlight brightness values, however, this did not significantly change the results, thus we include locations with zero nightlight brightness in the analysis.

3. Results

3.1. Night lights and damage zones

There were significant differences in nighttime light brightness from 2004 to 2008 (ANOVA $F = 6.03$, $p < 0.001$) (table 1). There was no significant difference in the brightness in the areas that were moderately, lightly or not damaged before the tsunami (figure 3a). After the

tsunami (2005), the lights were one-third less bright on average in every damage zone and the proportionate decline between 2004 and 2005 was approximately the same in each damage zone (figure 3b). By 2006, the night light index returned to its pre-tsunami level in every damage zone and remains relatively stable after that in every area other than the heavily damaged area. The brightness index continues to increase in the heavily damaged areas after 2006. By 2007, nightlight brightness was greater than pre-tsunami levels and further increased in 2008 (figure 4).

3.2. Relationships between night light brightness and economic activity

The coefficient between $\ln(\text{PCE})$ and night-time light brightness was positive and statistically significant ($p < 0.001$) in every year (table 2). The relationship between the light brightness and $\ln(\text{PCE})$ was much flatter in 2005, relative to 2004 and by 2006 it has returned to a slope that was very similar to that in 2004, before the tsunami. The slope continues to increase and then stabilizes at a higher level than before the tsunami. When nightlights were related to expenditures on utilities and food expenditures (table 2). There were significant ($p < 0.001$) relationships with both metrics but the amount of variance that can be explained by the night light brightness was less for food expenditures.

4. Discussion

4.1. Nightlights and damage zones

Nightlights appear appropriate for quantifying the macro-level impact of the tsunami and the subsequent reconstruction. Before the tsunami, nightlights were much brighter in the areas that were subsequently heavily damaged. This reflects the fact that the coastal areas are more developed and used more energy than the inland areas that were off the electric grid. The coastal city of Banda Aceh, was both a source of much of the nightlights and sustained heavy damage (Doocy *et al.* 2007, Frankenberg *et al.* 2008). However, it is not just Banda Aceh. In rural areas, the differences across damage zones were smaller in magnitude, but significant. In 2005, the lights were about one-third less bright on average in every damage zone and the proportionate decline between 2004 and 2005 was approximately the same in each damage zone. The decline in average brightness between 2004 and 2005 was seen in both urban and rural areas. However, nightlight missed approximately 30% of the communities due to zero digital brightness values.

By 2006, the light index returned to its pre-tsunami level in every damage zone and remains relatively stable after that in every area other than the heavily damaged area. The brightness index continues to increase in the heavily damaged areas after 2006. One interpretation of this is that post tsunami reconstruction resulted in greater levels of economic activity (or energy use) than before the tsunami and that this reconstruction was concentrated in those areas that were heavily damaged. However, the removal of trees from the tsunami could have also resulted in increase brightness in heavily damaged areas. Either way the relative return (< 2 years) rate of nightlights suggests a rapid return of physical infrastructure.

Comparing DMSP-OLS night light imagery before and after natural hazards is a standard and repeatable method to compare damage and reconstruction at a global spatial scale. Cross-calibrated nightlight brightness values since 1994 (Elvidge *et al.* 2009) can be

compared for all areas where significant natural disaster have occurred and comparative estimates of damage and reconstruction can be undertaken. However, there were some limitations with using nightlights for assessing damage from natural disasters. There were a high proportion of communities with zero digital number brightness values in Sumatra that were missed when assessing the impact of damage using nightlight imagery and this will be the case for regions, especially in the tropics. Thus damage and reconstruction estimates using DMSP nightlights dataset should assume that only communities and households on the electric grid are assessed.

4.2. Relationships between night light brightness and economic activity

Percentage changes in PCE, provide evidence on the massive impact of the natural disaster. Overall, PCE fell by 25% in the year after the tsunami, by 36% in the most heavily damaged areas and by 15% in areas that were not directly affected. These are dramatic declines in PCE. To put them in perspective, PCE fell by 15% during the 1998 financial crisis in Indonesia that presaged the end of the Suharto government. In the United States, GDP fell by a total of 15% during the three years of the Great Recession following the 2008 financial crisis. While PCE has grown in all four damage zones, it has not grown above its pre-tsunami level and growth in the heavily damaged areas does not match the growth seen in the nightlight brightness. This suggests that use of energy (or the measure of activity that is captured by the night lights) has increased more rapidly than the rate of growth in higher PCE areas relative to lower PCE areas. It should be noted that the R^2 values between household and community surveys are much lower than those surveys of cities in developed nations ($R^2 > 80\%$) (Elvidge et al. 1997; Doll et al. 2006). Thus although nightlights can be used as a community level economic metrics from household surveys, the current resolution of the nightlight data is only able to explain 20% of the variance in economic activity. The correlations are lower because there are many factors that affect nightlight brightness. Total spending, spending on utilities or spending on food are only a subset of those factors. Population size and density, small number of surveys within single nightlight pixels, and extent of infrastructure are other important factors that affect measurement error. The evidence, however, indicates that nightlights are highly correlated with our measure of economic activity although proportionate reductions in nightlights are greater than proportionate reductions in PCE in the presence of large shocks to the local economy.

5.0 Conclusion

Our research suggests that DMSP-OLS annual night light imagery can be used to assess the temporal path of recovery after a natural disaster and these metrics are well matched to changes in economic activity in the community. Given the spatially explicit nature of the Defense Meteorological Satellite Program Operational Linescan System data, it is theoretically possible and practically feasible to assess the rate of recovery for all regions on the electric grid that have experienced a significant natural disaster with little delay and at very low cost. In contrast with mounting a household survey, which takes months to plan and implement and calls for substantial financial outlays, the use of nighttime light imagery relies on freely available data that are placed in the public domain with a very short lag.

Nighttime light imagery is a potentially useful tool for tracking change in situations where complementary data are difficult to collect.

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Figure 1.
Study area in Sumatra, Indonesia and 307 STAR survey stations (red dots).

Figure 2.
Infrared MODIS imagery (250 pixel resolution, band 1 and 2) of Banda Aceh, Indonesia from before (a) and after (b) the tsunami and locations of STAR survey stations (white cross) used to assess the extent of damage.

Figure 3. DMSP-OLS F16 nighttime light imagery and 307 STAR points from 2004 (a) and 2005 (b).

Figure 4. Mean nighttime light brightness (digital number) from STAR survey stations (2004 to 2008) and number of pixels converted to bare earth after the tsunami.

Table 1

Nighttime light brightness values (digital number) in damage zones each year from 2004 to 2008. (Standard errors in parentheses)

Damage zones	Nighttime light brightness values by year			
	2004	2005	2006	2007
Heavy	14.6 (1.24)	11.6 (1.04)	16.4 (1.40)	16.5 (1.36)
Moderate	6.5 (1.21)	5.0 (1.01)	6.4 (1.37)	6.4 (1.33)
Light	8.1 (1.17)	6.2 (0.98)	7.3 (1.32)	7.7 (1.28)
None	5.7 (1.47)	4.6 (1.23)	5.0 (1.66)	5.4 (1.62)
				4.6 (1.75)

Table 2

R² of the regression between 307 nighttime light brightness values (digital number) and three measures of economic activity: log per capita expenditure (ln(PCE)), log per capita utilities expenditure (ln(xutil)), log per capita food expenditure (lnx(food)) from 2004 to 2008. All relationships were statistically significant ($p < 0.001$).

Economic activity	Correlation (R^2)				
	2004	2005	2006	2007	2008
ln(PCE)	0.23	0.14	0.24	0.28	0.24
lnx(util)	0.27	0.09	0.21	0.27	0.25
lnx(food)	0.11	0.13	0.14	0.19	0.14