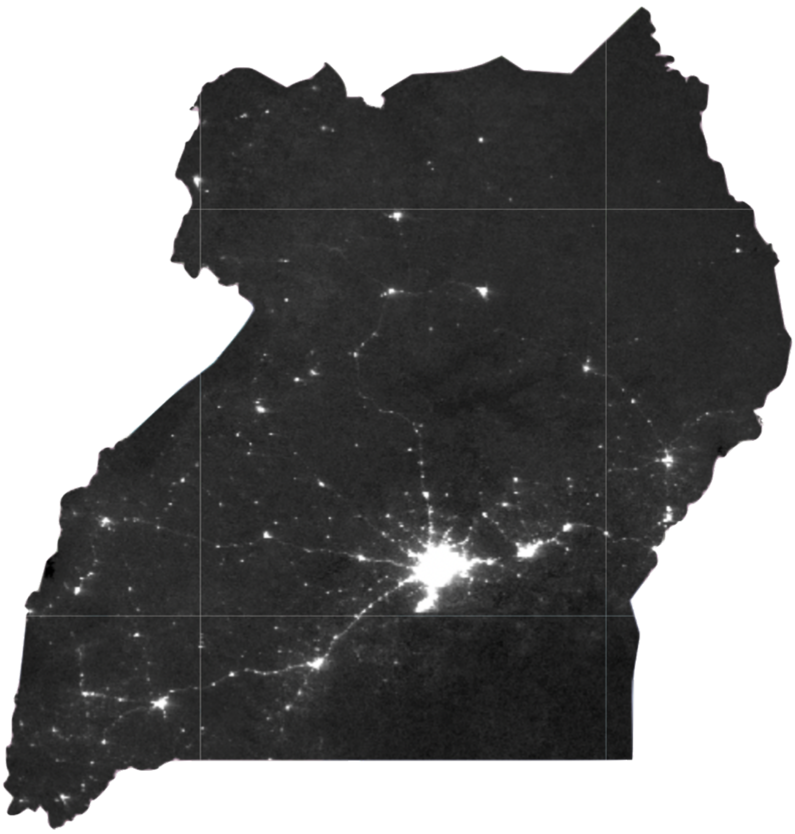
Lund University | Department of Economics

NEKH01 | Bachelor's thesis

May 2022

Night-time lights as a proxy for socioeconomic indicators in Uganda



Author: Eric Kaoukji

Supervisor: Petra Thiemann

Abstract

A large amount of economic research is reliant upon census, survey, or national accounts as a source of data. For many developing nations, the quality of this data is widely recognised to be unreliable and is rarely available at the sub-national level. By using a new and improved source of night-time satellite imagery data, this study investigates to what extent this data can serve as a proxy to traditional means of measuring socioeconomic indicators in Uganda, as well as what improvements this new source of data offers over it's more widely used predecessor. For the purpose of this study, an algorithm is constructed that sources, pre-processes, and converts satellite image data into a product ready for analysis. The relationship between night-time lights and the chosen indicators is investigated by conducting a series of linear regressions, and the ability of this new data source to detect small-scale change in night-time lights is explored through the creation of a "rate of change" map. This paper concludes that there exists a strong, substantial relationship between night-time lights and GDP, life expectancy, infant mortality rate, access to electricity, and urban population in Uganda. Furthermore, this paper concludes that this new source of satellite data allows for the detection of change in night-time lights at a spatial resolution far higher than what was previously possible with the older source of night-time light data.

Keywords: *Night-time lights, Remote sensing, Uganda, Development economics, Python, Linear regression, Satellite imagery.*

Acknowledgements

I would like to thank my supervisor Petra Thiemann for her continuous support and guidance throughout the process of constructing and writing this paper.

Table of Contents

Abstract *2*

Acknowledgements *3*

1. INTRODUCTION *5*

2. BACKGROUND *7*

2.1 Remote Sensing & Night-time Lights 7

3. LITERATURE REVIEW *8*

3.1 Night-time lights as a proxy 8

3.2 Application in economic research 11

3.3 VIIRS-DNB: A vast improvement over DSMP-OLS 12

4. DATA *13*

4.1 VIIRS-DNB 13

4.2 Indicators 15

4.2.1 GDP & GDP per capita 16

4.2.2 Life Expectancy & Infant Mortality Rate 16

4.2.3 Access to Electricity & Total Urban Population 17

5. METHOD *18*

.... 18

.... 18

5.1 Data Collection & Conversion 19

5.2 Regression analysis 20

5.3 Rate of Change Map 21

6. RESULTS *22*

6.1 National level results 22

6.2 Sub-national level results 25

7. DISCUSSION *29*

7.1 National level 29

7.2 Sub-national level 30

7.3 Limitations 32

VIIRS-DNB 32

7.3.2 Agricultural land-use 33

7.3.3 Transferability to other countries 33

7.4 Future research 34

8. Conclusion *35*

9. References *37*

10. Appendix *39*

1. INTRODUCTION

One of the biggest challenges in economic research is improving the quality of economic data, especially for developing economies. Many developing countries, particularly those ravaged by conflict, have little or no reliable sources of census or economic data. Low quality of data has made attempts to understand growth, development, and poverty difficult at best, and has greatly hindered research at the subnational level. The increasing availability of high-quality remote sensing data[1] presents a unique opportunity for researchers and organizations alike to combat the issue of poor data quality in developing nations, as well as provide an alternative means for accurately and effectively measuring socioeconomic variables such as Gross Domestic Product, life expectancy, and urban population.

Should data derived from remote sensing prove to serve as an effective proxy for socioeconomic indicators, the potential savings in cost associated with gathering economic and demographic data could be tremendous. Since many encompassing, high-quality, remote sensing datasets are publicly available, the principal costs associated with traditional data collection in developing nations could effectively be bypassed by anyone with an internet connection and a computer. Furthermore, being able to produce an accurate picture of where growth, development and poverty is most prevalent on a subnational level would further improve the effective allocation of aid and resources by humanitarian organizations equipped with the knowledge of where their resources can be most effectively applied. Finally, being able to more accurately study and understand economic growth and development as a result of higher data quality would serve to further the field of economic research as a whole, since this would open the door to future research investigating relationships and phenomena that have yet to be studied.

Building on the presumption that most economic activities require electricity, this paper aims to contribute to the ongoing research regarding night-time light data as a proxy for socioeconomic indicators by using a new source of satellite imaging data considered to be a vast improvement over that used in the majority previous studies. This will be done by using the Python programming language to source night-time satellite data from the VIIRS-DNB[2] sensor via the Google Earth Engine (GEE) API[3], and then constructing an algorithm to pre-

[1] Information acquired using satellites, high-flying aircraft or other sensor carrying devices.
[2] Visible and Infrared Imaging Radiometer Suite – Day Night Band sensor.
[3] Application Programming Interface, a server that allows the user to send and retrieve data using code.

process and convert this data into a product ready for analysis. This data will be used to conduct a series of linear regressions on a selection of national level socioeconomic indicators in Uganda, to determine the relationship between night-time lights and these indicators. Thereafter, a map visualizing the rate of change in night-time lights during the period 2014-2020 will be constructed using the same source of data to offer insight into how night-time lights have developed in Uganda on a sub-national level. By conducting this analysis, this paper aims to investigate if night-time lights measured by the new VIIRS-DNB sensor can offer improvements upon the results found in previous studies using the DMSP-OLS[4] sensor, as well as to which extent night-time lights can serve as a proxy for socioeconomic indicators.

Uganda has been chosen as the subject of study in this paper for a few reasons. Firstly, the nation is widely considered to be one of the poorest and least developed countries in the world[5]. The country still faces many key development challenges including poverty, low investments in infrastructure, and economic vulnerability. Additionally, despite decent diplomatic and trade relations with neighbouring countries to the west and south, Ugandan intervention in the South Sudan civil war has resulted in clashes and conflict between rebels and military being a frequent occurrence in areas near the border since 2013[6]. However, in terms of the World Bank's Statistical Capacity Score[7] Uganda is considered to have some of the highest quality socioeconomic data in the continent (see *Figure 2*). Although this statement may at first seem to contradict the purpose of this paper (to investigate the usefulness of night-time lights as a proxy in countries with poor economic data), the choice of a developing nation with high quality economic data has been an active one. By conducting a linear regression on accurately measured socioeconomic indicators in a developing nation, this paper will be able to form a more decisive conclusion regarding how closely the former reflects the latter, and thereby how well night-time lights can serve as a proxy measurement in nations lacking reliable sources of socioeconomic data. Conducting this same analysis on a nation with poorer data quality would mean that any inference made regarding how well night-time light data reflects traditional measurements would be, inherently, unreliable.

[4] Defense Meteorological Satellite Program – Operational Linescan System: A satellite sensor that has been in operation since the 1970's, considered the VIIRS-DNB's predecessor.
[5] UN Economic profile for Uganda: https://www.un.org/development/desa/dpad/least-developed-country-category-uganda.html
[6] Source: https://www.accord.org.za/conflict-trends/south-sudan-uganda-relations/
[7] An indicator measured by the World Bank assessing a nation's ability to collect, analyse, and disseminate high quality data about its population and economy.

2. BACKGROUND

Since it cannot be expected of everyone reading this to be familiar with some of the aspects discussed in this paper, the key terms, and topics essential to understanding the coming sections will be briefly presented and explained below.

2.1 Remote Sensing & Night-time Lights

Remote sensing refers to the acquisition of information on an object of study without coming into physical contact with the object in question. Typically, the term is used to refer to acquiring information about the Earth using satellites, high-flying aircraft, or other sensor-carrying devices. Sensors used in remote sensing can be divided into two main categories: Passive and Active. Passive sensors measure natural sources of energy that are emitted or reflected off the surface of the Earth, such as sunlight or city lights, whereas active sensors use their own source of energy for illumination (e.g. RADAR, LIDAR). Although Remote sensing is an umbrella term that can refer to many different types of information acquisition, the term will in this paper be primarily used in a context referring to information collected by sensors on board satellites.

Night-time lights, or remotely sensed night-time light data, refers to low-light imaging of the Earth from space. Low-light imaging from satellites has been conducted since the 1970s following the introduction of sensors on board the Defence Meteorological Satellite Program (DMSP) and has been used to capture various sources of low-light emissions from Earth[8]. Low-light emissions from Earth at night often indicate aspects of human activity, as sources of these emissions include gas flares, fishing boats, and city lights to name a few[9]. By capturing these low-light emissions, night-time lights provide an opportunity to gain insight into human activity, as the sources associated with the observation of artificial lighting at night include commercial activity, contemporary urban settlements, and transportation corridors. The connection between night-time lights and economic activity, urbanization and development will be further examined and corroborated in the literature review section.

[8] https://eogdata.mines.edu/products/dmsp/

[9] Elvidge, C. D., Baugh, K. E., Kihn, E. A., Kroehl, H. W., & Davis, E. R. (1997). Mapping city lights with nighttime data from the DMSP Operational Linescan System. *Photogrammetric Engineering and Remote Sensing*, *63*(6), 727-734.

3. LITERATURE REVIEW

There exists already an extensive literature in which many studies have shown night-time lights to be highly correlated with presence of population, economic activity, GDP, and GDP growth. This section will present and summarise a portion of the studies that have laid the groundwork for the ongoing research regarding the applicability of night-time lights as a useful proxy for socioeconomic indicators.

3.1 Night-time lights as a proxy

Since it was first implemented in the 1970's, the DSMP – Operational Linescan System (OLS) was capable of capturing daytime and night-time imagery of the Earth through two spectral bands, VIS and TIR (Elvidge et al., 1997). The signal from the VIS band, used for capturing night-time imagery, is intensified using a photomultiplier tube (PMT) to capture low-light emission sources. The PMT system was initially implemented to detect cloud coverage at night, however, an unintended consequence of the intensification of night-time light was the ability to detect gas flares, city lights and fires at night. Despite the potential use of DMSP-OLS data for monitoring city lights and other low light emission sources being noted as early as the 1970's, no digital archive of the DMSP-OLS was kept for the first 20 years.

In 1997, Elvidge et al. (1997) created a digital method for mapping city lights with DMSP-OLS by excluding lights diffused by cloud coverage, thereby creating a reliable way to observe and monitor city lights at night. The creation of this digital method opened the doors to the research community to utilize night-time light data to effectively map stable low light emission sources.

Building on the method developed by Elvidge et al. (1997), Doll et al. (2000) exploit night-time satellite imagery to investigate the potential of night-time imagery for quantitative estimation of global socio-economic parameters. By utilizing 6-month composite night-time satellite images from which transient light sources such as bush fires and shipping fleets are eliminated, Doll et al. (2000) create a "stable lights" dataset, containing only light emitted from cities at night.

By comparing this "stable lights" dataset against a number of supporting datasets, Doll et al. (2000) are able to create estimations of global urban population that account for over 90% of the quoted total. Additionally, Doll et al. (2000) find that the total lit area of a country at night has a statistically significant high correlation value with Gross Domestic Product (GDP), as well as total carbon dioxide (CO_2) emission.

Similarly, Sutton & Costanza (2002) utilize the DSMP - OLS dataset to quantify a relationship between night-time lights and Gross State Product (GSP)[10] for the US states by regressing GSP with the measured night-time lights for each state. They find that a one-percent increase in Light Energy measured by the DMSP-OLS is associated with an increase in the GDP by 1.05 percent. They find an R-squared value from the regression of log Light Energy on log Gross State Product of 0.86, implying that 86 percent of the variance in Gross State Product is explained by Light Energy, signifying a substantial relationship.

Ebener et al. (2005) further examine the relationship between DMSP-OLS night-time light measurements and economic output by investigating if night-time lights, as a proxy for wealth, can in turn support the estimation of the distribution of correlated health-indicators at the national and sub-national levels. Ebener et al. (2005) demonstrate the usefulness of night-time lights as an independent measure, with zero reliance on national reporting data, as an effective method of generating estimates of both national and sub-national GDP per capita figures. Additionally, the country level results confirm the conclusion given by Doll et al. (2000) regarding the relationship between total area lit and GDP.

Furthermore, Ebener et al. (2005) find that night-time lights can be successfully used for the prediction GDP per capita until a certain level of economic development. Their results indicate that while the relationship between night-time lights and GDP per capita is strong in developing nations, this relationship breaks down as a nation reaches higher levels of economic development.

Ebener et al. (2005) conclude by emphasizing the importance of night-time lights as a method of evaluating the impact of international efforts to improve the economic and health conditions of people in the poorest areas of the world. Ebener et al. (2005) suggest that

[10] Measured as the Gross Domestic Product for an individual State in the USA.

improving the quality of night-light datasets may be a far easier way of improving the measurement of sub-national economic indicators rather than improving the national reporting of these indicators. Finally, Ebener et al. (2005) propose applying their approach to consumption indicators, instead of income per capita figures, as a method of generating country-specific poverty maps.

Ghosh et al. (2010) combine DMSP-OLS night-time satellite imagery with the LandScan population grid[11] dataset to create a model for estimating total (informal plus formal) economic activity for nations of the world. Similar to previous studies, Ghosh et al. (2010) find strong relationships between GDP and Sum of Lights measured by DSMP-OLS, finding an R^2 as high as 0.99 for some sample groups.

Ghosh et al. (2010) explain that their approach does not represent a truly independent method of measuring economic activity, as the only way to validate their results was by comparison to official GDP statistics and estimates of the informal economy. However, they conclude that the map of total economic activity created from night-time imagery and the LandScan population grid provides an effective alternative means of measuring economic activity, especially in the context of the 2008 global economic recession, where the importance of understanding the global distribution of wealth and economic recovery is greater than ever.

Finally, Ghosh et al. (2010) discuss the observational shortcomings of DMSP-OLS data, namely coarse spatial and temporal resolution, as well as a lack of on-board calibration. Ghosh et al. (2010) indicate that night-time light data acquired at a higher spatial and temporal resolution can potentially facilitate the creation of more accurate socio-economic maps, and believe that the introduction of the VIIRS satellite system will be able to address the shortcomings of DMSP-OLS nigh-time light data.

To summarise, previous studies have found that there exists a substantial connection between night-time lights and economic output, as well as great potential for the use of night-time lights measured by the DMSP-OLS as a method of measuring economic activity, health status and poverty in developing countries.

[11] A global population distribution database developed by the Department of Energy's Oak Ridge National Laboratory, available at: https://landscan.ornl.gov/

3.2 Application in economic research

In their extensive study, Vernon Henderson et al. (2012) create a statistical framework to combine data on changes in night-time lights using the DMSP-OLS with national accounts data on income growth to improve estimates of true income growth. Using this framework, Vernon Henderson et al. (2012) find that night-time lights growth can serve as an effective proxy for GDP growth in low-income countries. Vernon Henderson et al. (2012) conclude that night-time light data can play a key role in analysing growth at sub- and supra-national levels, where income data with high spatial resolution is unavailable. Furthermore, based on their findings, Vernon Henderson et al. (2012) suggest that future economic research on empirical growth no longer needs to be synonymous with national income accounts data.

Similarly, Nordhaus & Chen (2014), examine if night-time light data contains useful information for estimating national and regional incomes and output in economic research. Nordhaus & Chen (2014) find that there exists substantial information in night-time light data for countries with low-quality statistical systems, however, night-time light data provides little additional information for nations with more developed statistical systems.

Gibson et al. (2021), find in their study that although the DMSP-OLS is used far more often than the VIIRS-DNB as a source of night-time light data in economic research, VIIRS night-time light data serves as a much better proxy for local economic activity. However, they also find that despite VIIRS-DNB offering a vast improvement over the DMSP-OLS as a proxy measurement, there are still some questions regarding whether either of these sources can provide a good proxy for economic activity in low density rural areas. Instead, to construct a proxy measurement, Gibson et al. (2021), recommend the addition of other sources of daytime satellite imagery, in combination with traditional sources of survey data.

Furthermore, Gibson et al. (2021) note that although previous research has found promising results regarding the use of DMSP-OLS night-time lights to predict GDP at the national level, this may not be an appropriate justification for the use of the DMSP-OLS in more recent studies making predictions on the sub-national, or even pixel level. They note that although both sources of night-time data experience a decline in performance at lower-level spatial units, the VIIRS-DNB retains a much higher predictive performance than the DMSP-OLS at lower level spatial units, and suggest that the VIIRS-DNB is a much better source of data for studying spatial patterns of urban development.

In summary, night-time lights are considered to be state-of-the art in economic research, however, there are still open questions regarding their applicability and validity, especially in terms of spatial resolution. Despite the VIIRS-DNB being widely considered an improvement over the DMSP-OLS, some of the concerns regarding the application of night-time lights in economic research apply to both sources of data, and further research is necessary to point out their validity in different contexts. This paper will contribute to this expanding literature by investigating the applicability of night-time lights measured by the VIIRS-DNB as a proxy measurement in Uganda.

3.3 VIIRS-DNB: A vast improvement over DSMP-OLS

Despite shortcomings associated with DMSP-OLS data regarding spatial and temporal resolution in earlier research, many previous studies have not had access to another source of night-time light data. This has been because until 2011, DMSP-OLS was the only system collecting low-light imaging data of the Earth. In 2011 the first Suomi National Polar Partnership (SNPP) satellite carrying the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument was launched. Similar to the DMSP-OLS, the VIIRS carries a spectral band, the Day / Night band (DNB), which captures standard image data by day and low light image data by night. Night-time light data captured by the VIIRS-DNB is widely considered a tremendous improvement over the DMSP-OLS, especially in terms of spatial resolution (Elvidge et al., 2013). A more detailed comparison of these two data sources will be presented in the Data section below.

By addressing the shortcomings regarding the quality of night-time light data in previous studies through the newer, and vastly superior VIIRS-DNB sensor, this paper attempts to confirm and improve upon previous results regarding the validity of night-time light data as a proxy measurement.

4. DATA

4.1 VIIRS-DNB

Night-time imagery captured by the VIIRS-DNB offers a substantial improvement over that captured by the DSMP-OLS in terms of spatial resolution, dynamic range, and calibrations[12]. Night-time imagery is captured by the VIIRS-DNB at a ground footprint of 742 x 742 m, compared to the 5 km x 5 km ground footprint of the DMSP-OLS. The VIIRS-DNB pixel footprint[13] is thus 45 times smaller than the DMSP-OLS pixel footprint (see *Figure 1*.)

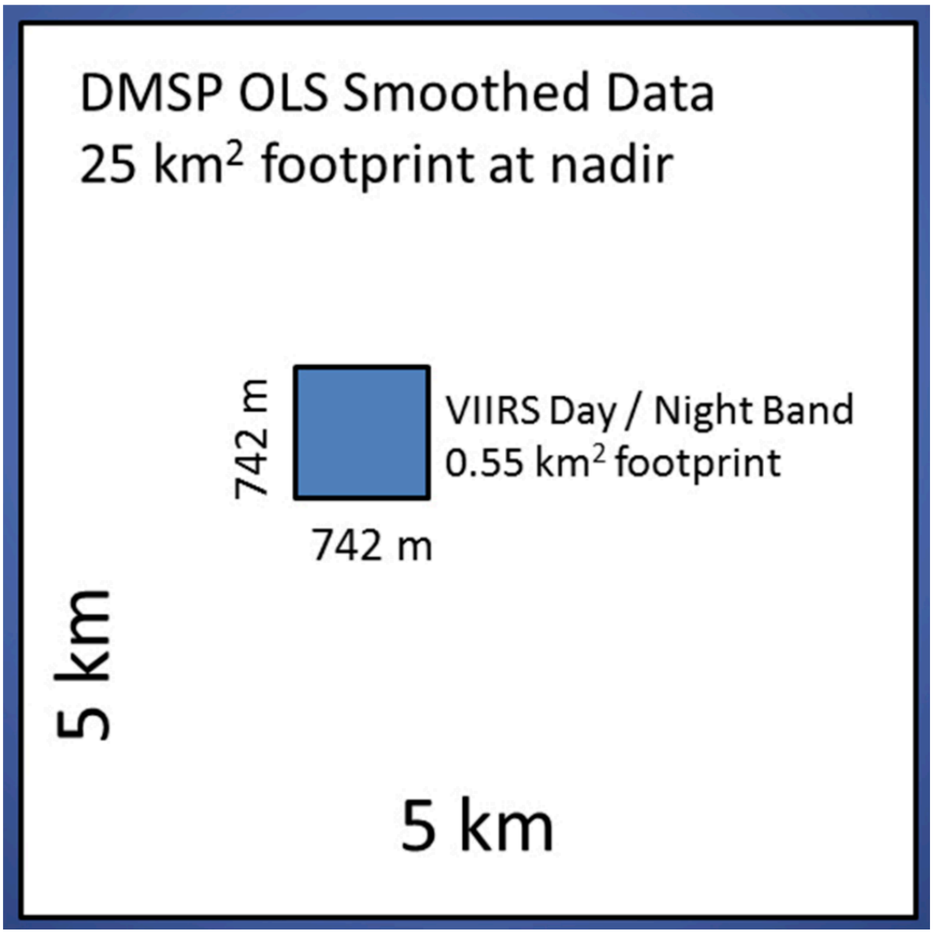


Figure 1. *Comparison of pixel footprint with which VIIRS-DNB & DMSP-OLS data are collected. Source: Elvidge, C. D., Baugh, K. E., Zhizhin, M., & Hsu, F. C. (2013).*

[12] Dynamic range refers to the range of light the sensor is capable of capturing, higher dynamic range means the sensor captures images with a higher contrast range between the lightest and darkest tones. In terms of calibrations, the VIIRS-DNB includes a solar diffuser that the DMSP-OLS does not, used to calibrate daytime data, which can be extend to low light imaging.

[13] Pixel footprint is interpreted as the effective size of one pixel in a captured image at ground level.

To illustrate the superiority of the VIIRS-DNB product, a comparison between VIIRS-DNB and DMSP-OLS was made, using a script written in Python. The data from both sources was processed identically, using a cloud free composite image[14] for the month of January for the years 2013 (DMSP-OLS) and 2014 (VIIRS-DNB). *Figure 2* shows a side-by-side comparison of the VIIRS-DNB image versus DMSP-OLS image for the Ugandan capital city, Kampala, in the month of January 2013 and 2014. Although the images have been taken one year apart, so a difference in night-time lights between the two images must be considered, the vastly superior detail of the VIIRS-DNB product is still clearly visible.

VIIRS-DNB: Kampala, January 2014 **DMSP-OLS: Kampala, January 2013**

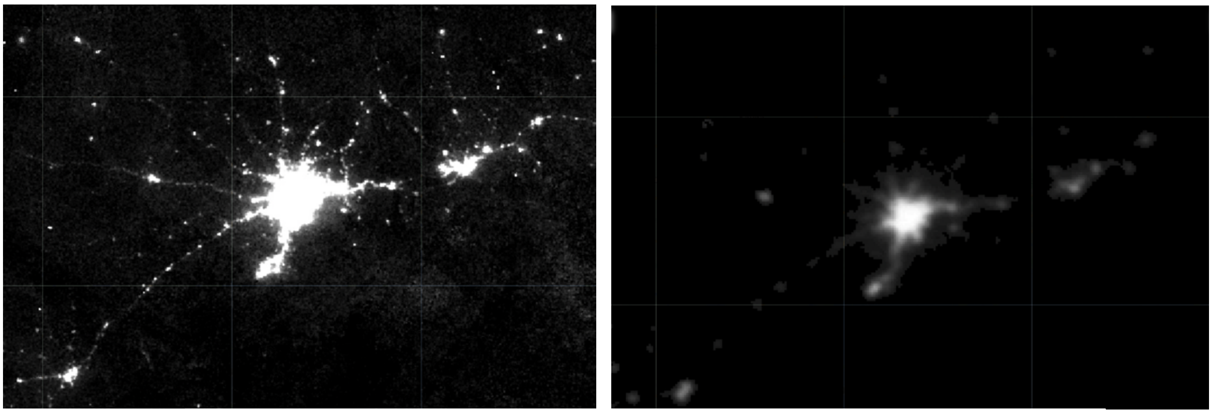


Figure 2. *Side-by-side comparison of VIIRS-DNB & DMSP-OLS.*

In the analysis, VIIRS-DNB data for the years 2014 through 2020 will be collected via Google's Google Earth Engine (GEE) API using Python. GEE offers access to many satellite imagery products, including both DMSP-OLS and VIIRS-DNB, with the added benefit of being able to access Google's digital infrastructure carry out extensive computations on these datasets. 'Night-time lights' will be measured as the sum of all average DNB radiance values for each month, expressed in terms of nanowatts per square centimetre per steradian[15]. This measurement will be referred to as the Sum of Lights (SOL). When initially accessed, the image data is stored in a raster format[16], however, this data will be converted into numerical values to facilitate analysis.

---

[14] A cloud free composite refers to a composite image of all images taken by the VIIRS-DNB during an individual month, excluding cloud coverage.

[15] The steradian, or square radian, is the SI unit of solid angle and is frequently used in three-dimensional geometry

[16] Raster is one of the main file formats for digital images. A raster file stores a two-dimensional image as a rectangular matrix of equally sized cells, where each cell is associated with a geographical region and the value in that cell represents some characteristic of that region.

4.2 Indicators

To measure the relationship between VIIRS-DNB night-time light data and economic indicators, a collection of indicators deemed important for understanding the development, economic activity, and general health status of a nation have been selected for the years 2014 through 2020. The indicators; Gross Domestic Product (GDP), GDP per capita, Life Expectancy, Infant Mortality Rate, Access to electricity, and Total Urban Population have been chosen for Uganda. As mentioned in the Introduction section, Uganda has been chosen both for its status as a developing nation, in combination with its high level of level of statistical capacity[17] relative to other Sub-Saharan African nations, as can be seen in *Figure 3*. All indicators have been sourced from the World Bank; they are measured on a yearly basis and available at the national level. Below, a brief presentation of each indicators unit of measurement as well as relevance will follow.

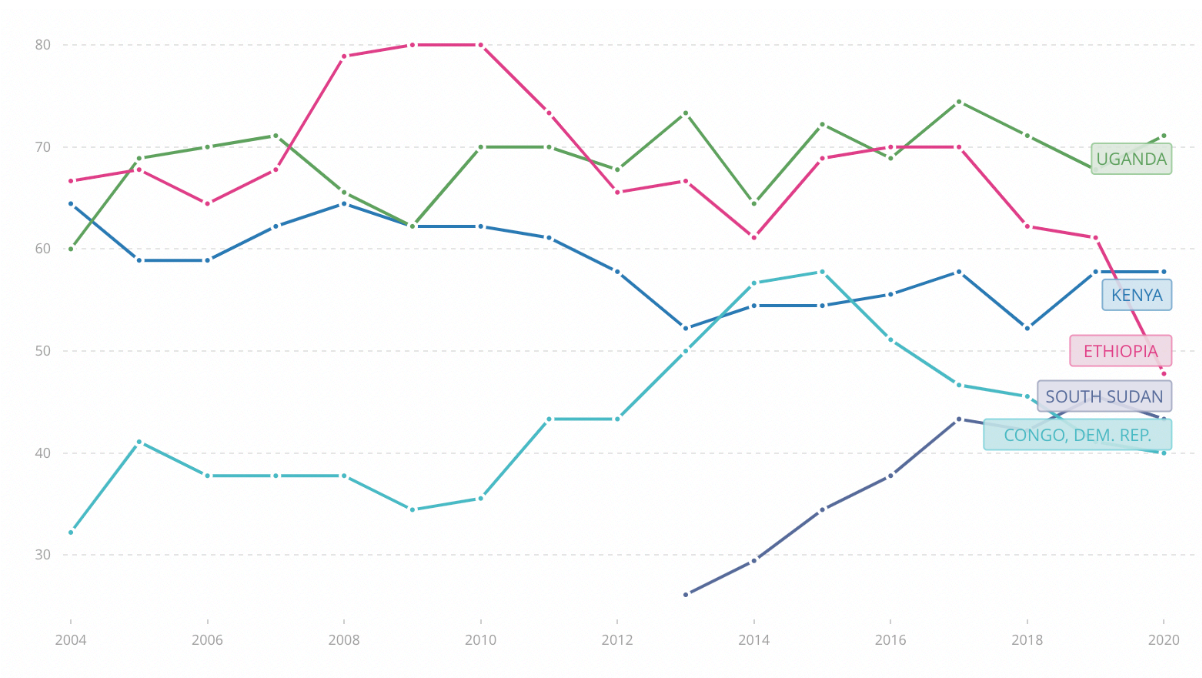


Figure 3. *A direct comparison between the World Bank's Statistical Capacity Score for Uganda and an arbitrary selection of Sub-Saharan African Nations. Source:* [*https://data.worldbank.org/indicator/IQ.SCI.OVRL*](https://data.worldbank.org/indicator/IQ.SCI.OVRL)

[17] As measured by the World Bank's Statistical Capacity Score

4.2.1 GDP & GDP per capita

Both GDP and GDP per capita are measured in constant 2015 US Dollars. Both indicators have been measured from World Bank national accounts data, and OECD National Accounts data files. GDP is measured as the total sum of all value added by producers in the economy, plus any product taxes and minus any subsidies not included in the value of products, and GDP per capita is simply the same measurement divided by population. These measurements have been converted from Uganda's domestic currency to dollar amounts using official 2015 exchange rates. However, since this analysis will only be comparing the same country over time, this conversion is not strictly necessary.

GDP & GDP per capita have been chosen since they represent reliable methods of measuring the growth of an economy, as well as granting insight into the income level of its residents. Since an economy's growth is measured by change in output or real income of its residents, both these indicators provide a means of measuring the general development of Uganda's economy over time, as well as studying if the development of night-time lights reflects that of the nation's economy.

4.2.2 Life Expectancy & Infant Mortality Rate

Life expectancy or Life expectancy at birth, is measured in years and indicates the expected number of years a new-born infant will live provided the general patters of mortality at the time of birth stay the same throughout its life. Infant Mortality Rate is measured as the number of infants that die before reaching one year of age, per 1,000 live births.

Mortality rates and life expectancy provide an overall indication of the health status in a country, in addition to being among the indicators most frequently used to compare socioeconomic development across countries. These indicators have been chosen to investigate if there exists any relationship between night-time lights and the general health status of a country over time. Note that the presumption here is not that higher light intensity at night creates a healthier population, but rather that increased night-light intensity indicates increased socioeconomic development, which is in turn associated with an improved health status.

4.2.3 Access to Electricity & Total Urban Population

Access to electricity is measured as the percentage of population with access to electricity. Since it is impossible to operate a factory, deliver goods, grow crops, run household appliances, or refrigerate food without using some form of energy, energy becomes almost necessary to enable economic growth. Electricity is in practice crucial for many basic activities and cannot easily be replaced with other forms of energy on the individual level. Individuals access to electricity thereby represents one of the most important indicators to measure the energy status of a country. Building on the presumption that increased access to electricity improves individual's standard of living, this indicator has been chosen to investigate if there exists a relationship between night-time lights and what percentage of the population has access to electricity. It is worth noting the difference here between access to electricity and total electrical consumption since total electrical consumption is assumed to be heavily correlated with night-time lights but does not offer as much insight into the development or living standards in a country (since large amounts of energy consumption can stem from individual sources that may not be contributing directly to increased standards of living).

Total urban population is measured as the amount of people living in urban areas as defined by Uganda's national statistical offices. Since this study will only examine one country, the total number of individuals is used. However, if one were comparing countries against each other, percentage of the population living in urban areas would be a more appropriate indicator. Since increasing urban population signifies a demographic transition from rural to urban, which is in turn associated with a shift from agriculture to industry and technology, this indicator provides an insight into the process of urbanization in a country. By studying the relationship between this variable and night-time lights, one can gain insight into how well the development of night-time lights measures urbanization.

Before moving forward, it is important to emphasize that this paper does not claim a causal relationship between night-time lights and these indicators, since the relationship can be argued to go both ways. Instead, the goal is to understand to which extent night-time lights can serve as a proxy for these indicators.

5. METHOD

This paper's analysis was conducted using an algorithm created in Python. The analysis can be said to consist of two parts: a national, and sub-national analysis, with more analytical emphasis laid on the national level. The goal of the national level analysis is to measure the relationships between night-time lights and the selected indicators in Uganda, whereas the goal of the sub-national level analysis is to lean on the results produced on the national level to explore where in Uganda change in night-time lights, and by proxy socioeconomic indicators, has occurred. On the national level, linear regressions for night-time lights measured by the VIIRS-DNB have been conducted for each indicator presented in the Data section above. For the sub-national level, a map visualizing the rate of change in night-time lights during the period 2014 through 2020 has been created. This section will describe the methodology behind both the national and sub-national analysis in detail. For readers looking for a more general outline of the methodology, a flow-chart has been created illustrating how the analysis has been conducted (see *Figure 4)*.

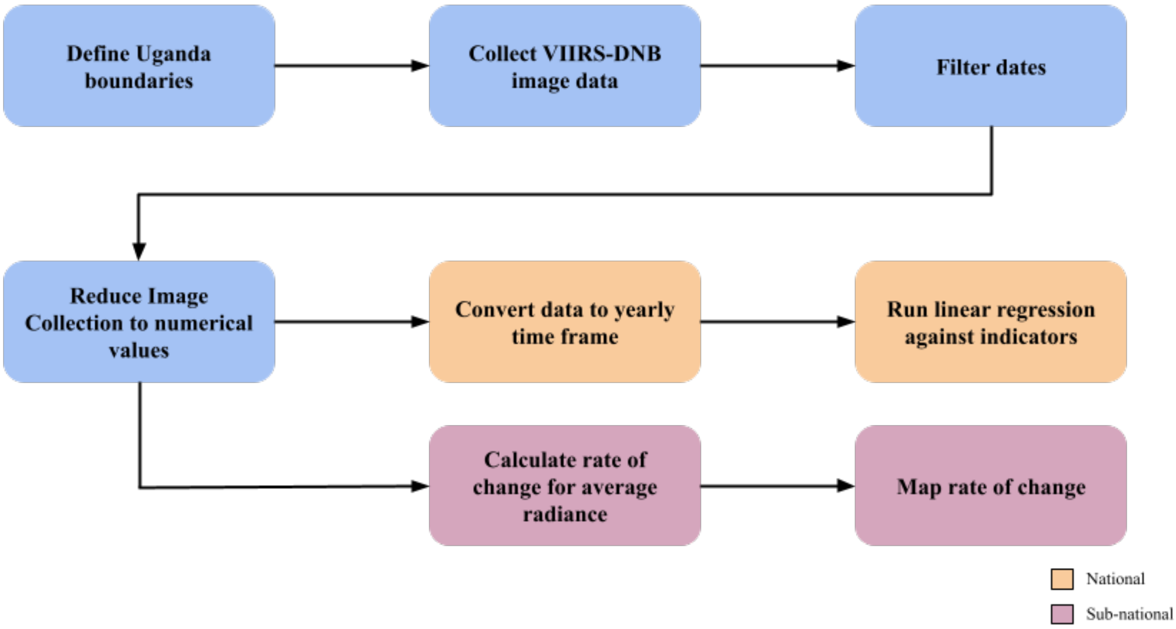


Figure 4. *A flow chart visualizing how the algorithm used in this analysis works. Blue stages are used for both the national and sub-national analysis, while orange stages are used on the national level and purple on the sub-national level.*

5.1 Data Collection & Conversion

To analyse the relationship between night-time lights and the selected indicators, the relevant VIIRS-DNB data must be collected and converted into numerical values. As mentioned in the Data section, this is done using the GEE API, a library imported into Python which allows the user to access and compute any of the datasets available on the GEE platform. Once the GEE API has been imported and initialized, a national boundary (also referred to as geometry) for Uganda is created in order to specify which area of the globe VIIRS-DNB data should be collected from. This is done to avoid computational restrictions associated with collecting VIIRS-DNB data for the entire globe. In this analysis, the borders for Uganda have been defined as shown in the United Nations Food and Agriculture Organization's Global Administrative Unit Layers dataset[18]. Additionally, the boundaries for Uganda were defined using a scale of 500 metres, effectively meaning that Uganda's borders were drawn using 500 metre lines. While the choice of scale when analysing the same country over time doesn't affect the results so long as it is kept consistent, it is a measure to be aware of when comparing countries against each other, as using different scales or different sizes of countries can produce wildly different results.

Once the boundaries for Uganda have been defined, the VIIRS-DNB data is collected for the specified boundaries and dates (2014 through 2020). Here, the average radiance band is selected, creating a collection of monthly composite images showing the average DNB detected radiance for each month in the specified period (See *Figure 5*).

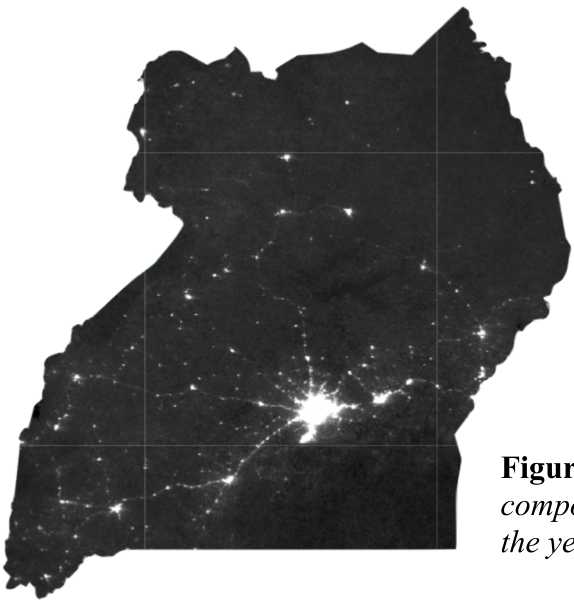


Figure 5. *An example of one of the monthly composites in the image collection produced for the year 2019.*

[18] Available at: https://data.apps.fao.org/map/catalog/srv/api/records/9c35ba10-5649-41c8-bdfc-eb78e9e65654

When initially collected, the image data is stored in a raster format, which needs to be converted into numerical values to be able to perform a linear regression. The numerical measurement for night-time lights chosen in this paper is referred to as Sum of Lights (SOL). The SOL represents the sum of all average radiance detected within the specified boundaries for a given month[19]. To calculate the SOL, a reducer function[20] built into the GEE API is applied to the raster files, then a time series is created containing the calculated SOL for each given month in the collected data.

At this point a monthly time series for the SOL in Uganda has been produced. However, before linear regressions can be performed this time series needs to be converted to a yearly time frame to match the indicator data collected from the World Bank. This is done by simply taking the mean SOL for each 12 months, resulting in a yearly time series for the SOL in Uganda.

5.2 Regression analysis

To conduct the national level analysis, a series of linear regressions are conducted. Each indicator sourced from the World Bank is set as the dependent variable using the relationship:

$$Y = \alpha + \beta \times \ln(SOL) + \varepsilon$$

Where Y refers to the indicator or dependent variable in question, α to the intercept, β to the slope of the regression, and ε to the error component. For each linear regression conducted, the intercept, slope, correlation coefficient (R), coefficient of determination (R^2), and p value of the regression is collected and stored in the table shown in the Results section. The explanatory variable for each regression is set as the log-transformed SOL, or $\ln(SOL)$. The log of SOL has been used as the explanatory variable mainly for the sake of interpreting the results in a clear way, using $\ln(SOL)$ as the explanatory variable allows the slope, or β of a regression, to be interpreted as the associated increase in Y when the SOL increases by one percent. Similarly, certain indicators that exhibit an exponential, or non-linear growth have been log-transformed as well. The transformed indicators are the following: *GDP, GDP per capita,* and *Urban Population.*

[19] When working with the same country over time, the SOL is an appropriate measurement. However, if one were to compare countries against each other, the mean of the average radiance would be a more appropriate measurement.
[20] A pre-written function in Python that reduces all raster files in the image collection to the sum of all average radiance values in each "cell" of the raster file.

The values collected from each regression are what will be used to determine and interpret the relationship between night-time lights and their respective indicator. The intercept and slope are used to determine the nature of the relationship, while the correlation coefficient, coefficient of determination, and *p* value will be used to determine the strength and significance of the relationship.

5.3 Rate of Change Map

For the sub-national level analysis, a map visualizing the rate of change in average radiance for the entire country of Uganda is created. This is done by subtracting the last composite image in the collection (December 2020) with the first composite image (January 2014), then dividing the result by the number of total images in the collection (84 images for 84 months). This results in a raster file containing the "slope", or rate of change for each pixel during this period, which is then, using Python, converted into an interactive map showing where in Uganda average radiance has increased or decreased. Owing to the high spatial resolution of the VIIRS-DNB, this allows the viewer to observe the rate of change all the way down to the neighbourhood level[21]. As mentioned above, no further numerical analysis was conducted on the sub-national level. The sub-national level analysis aims instead to illustrate the potential applications of such a map, by leaning on the relationships shown on the national level to precisely identify areas in a country where a change in night-time lights, and by proxy socioeconomic indicators, has occurred.

[21] Roughly 1km by 1km.

6. RESULTS

This section will present and explain the results of both analyses presented in the Method section above. For the national level, the results and coefficients of each linear regression will be presented and interpreted, whereas the sub-national level results will be presented in a more exploratory fashion, by interpreting some illustrative examples found in the generated map.

6.1 National level results

The results of each individual regression conducted can be seen in *Table 1.* As mentioned in the Method section, but not seen in the table, the log-transformed SOL has been used as the explanatory variable for every regression conducted.

	Dependent variable					
	ln(GDP)	*ln(GDP per capita)*	*Life expectancy*	*Infant mortality rate*	*Access to electricity*	*ln(Urban population)*
Slope	0.127 (0.041)	0.027 (0.013)	1.409 (0.386)	-4.117 (1.098)	13.346 (3.488)	0.168 (0.047)
Intercept	22.789 (0.481)	6.439 (0.155)	45.657 (4.583)	84.757 (13.036)	-126.352 (41.416)	14.079 (0.560)
R	0.814	0.680	0.853	-0.859	0.863	0.847
R2	0.662	0.462	0.727	0.738	0.745	0.717
Significance level	**	*	**	**	**	**
Sample mean	24.293	6.761	62.371	35.929	31.917	16.071
Number of observations	7	7	7	7	7	7

Table 1. *Results of the linear regressions conducted on the selected indicators. Standard errors are shown in parentheses. Note: $p < 0.1$:*, $p < 0.05$:**, $p < 0.01$:****

Working from left to right, beginning with *ln(GDP)*, we can see that the regression has resulted in a slope of 0.127, implying that a one percent increase in the SOL in Uganda is associated with 0.127% increase in the nation's GDP. Furthermore, the correlation coefficient, or R value between the two variables is 0.814, signifying a strong positive correlation between the variables. Finally, with an R^2 value of 0.662, meaning that roughly 66% of the variance in *ln(GDP)* can be explained by the SOL, as well as a p-value of 0.026, one can conclude that there exists a substantial, significant positive relationship between the SOL and GDP in Uganda.

When the dependent variable is set as the log of Uganda's GDP per capita, the regression results in a slope of 0.027, meaning that a one percent increase in SOL is associated with a 0.027% increase in the GDP per capita. An R value of 0.680 and an R^2 of 0.462 indicate that although there exists some sort of positive relationship between the SOL and GDP per capita, it is not nearly as strong as the relationship between the SOL and GDP Uganda. The uncertainty regarding the strength and existence of a positive relationship between SOL and GDP per capita is further confirmed by the regressions relatively high p-value of 0.09.

Setting Life Expectancy as the dependent variable results in a slope of 1.409, showing that a one percent increase in the SOL for Uganda is associated with roughly a 1.4-year increase in life expectancy at birth. Additionally, a 0.853 correlation coefficient as well as a R^2 value of 0.727 speak to the strength of this relationship. A p-value of 0.014, in combination with high R and R^2 values allows one to conclude the existence of a substantial positive connection between the SOL and Life expectancy in Uganda.

The linear regression on Infant mortality rate results in a slope of -4.11, implying that a one percent increase in the SOL is associated with a decrease of roughly 4 infant mortalities per 1,000 live births in Uganda. The R value of -0.859 indicates a strong negative relationship between the variables, which is supported further by the R^2 of 0.738 and p-value of 0.013.

When it comes to the relationship between the SOL and Access to electricity, the results of the regression indicate a substantial positive relationship, with a slope of 13.346 implying that a one percent increase in the SOL is associated with roughly a 13% increase in the portion of the population with access to electricity. Although the high R and R^2 values of 0.863 and 0.745 respectively speak to the strength of the relationship, and the low p-value of

0.012, it is worth noting the intercept of -126.352. This large negative intercept effectively implies that if there weren't any night-time lights in Uganda, -126% of the population would have access to electricity, which is of course highly unrealistic. Despite the other results of the regression indicating a strong and significant connection existing between the SOL and Access to Electricity in Uganda, the highly unrealistic intercept value illustrates the dangers of using such small sample sizes to predict unknown values.

Finally, regarding total Urban Population, the log-transformed version of the dependent variable is used since Urban Population is assumed to grow at an exponential rate[22]. The linear regression on *ln(Urban Population)* results in a slope of 0.168, meaning that a one percent increase in the SOL is associated with a 0.168% increase in the amount of individuals living in urban areas. An R value of 0.847 and an R^2 of 0.717 speak in favour of the existence of a strong positive relationship between the SOL and Urban Population, which is further corroborated by a p-value of 0.016 for the regression.

In summary, the linear regressions conducted for this paper's national level analysis find substantial, positive relationships between the SOL and GDP, Life Expectancy, Access to Electricity as well as Urban Population in Uganda. Furthermore, the analysis finds a strong negative relationship between the SOL and Infant Mortality Rate. Finally, although this analysis finds indications of a potential positive relationship between the SOL and GDP per capita in Uganda, in terms of the R, R^2 and p-value, this relationship cannot be considered as strong or substantial as the others.

[22] This assumption is made from initial exploration of the data provided by the World Bank.

6.2 Sub-national level results

As mentioned earlier, the purpose of the sub-national level analysis is to build upon the results found on the national level to make inferences regarding the development of smaller regions in Uganda. Building upon the results found on the national level, one can assume that an increase in the SOL during the period 2014-2020 will be associated with an increase in GDP, Life Expectancy, Access to Electricity and Urban population, as well as a decrease in Infant Mortality Rate. More broadly, the assumption is made that an increase in the SOL is associated with an increase in economic output, health status and standard of living. It is upon these assumptions that the map created visualizing the rate of change of the SOL in Uganda will be explored.

The map visualizing the rate of change has been colour-coded to illustrate which areas have seen an increase or decrease, where red pixels indicate a total increase in the SOL during the period 2014-2020, and blue pixels indicate a decrease. The intensity of the pixels colour indicates how drastic the change has been, with a more intense red or blue indicating a more rapid change in the SOL. Since the change is visualized on the pixel level, the high spatial resolution of the VIIRS-DNB allows the viewer to see changes all the way down to the neighbourhood level, however, this also means that it is extremely difficult to provide a visualization of the entire country of Uganda, as the map would appear blank without zooming in to at least the city-level. Therefore, the decision has been made to only show certain example areas of the generated map deemed interesting for this thesis's purpose. These examples can be seen in *Figure 6, Figure 7, Figure 8* and *Figure 9,* with further examples for those interested being available in the Appendix.

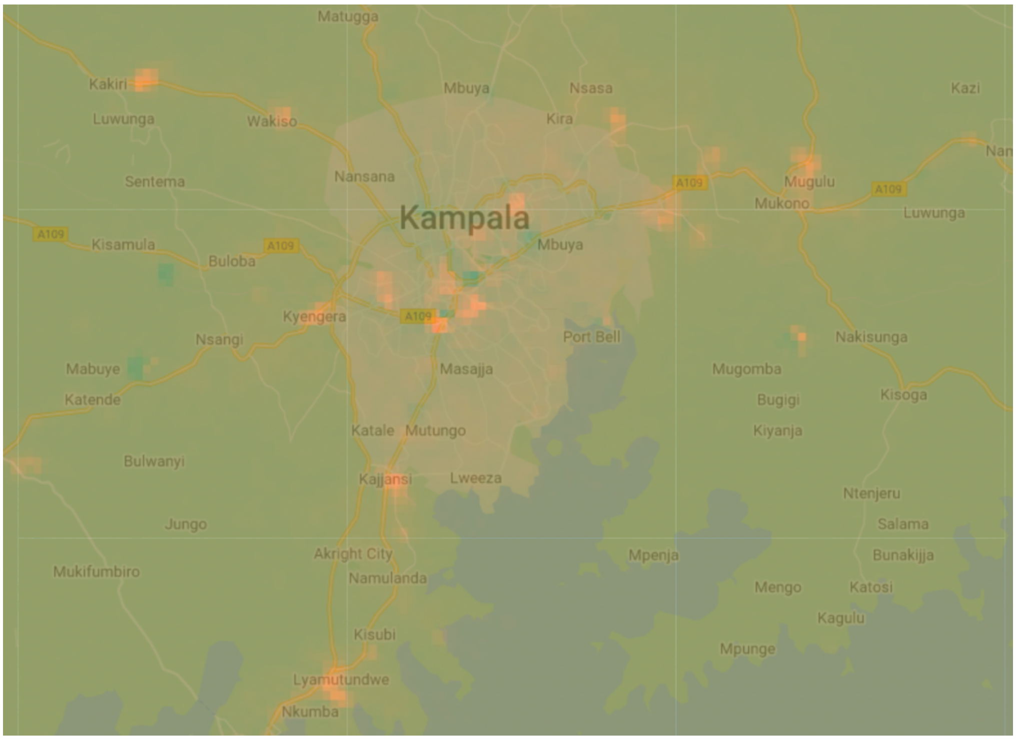


Figure 6. *Rate of change map centered on the capital city Kampala. Red pixels indicate positive rate of change, blue pixels indicate negative. Background map provided by Google Maps.*

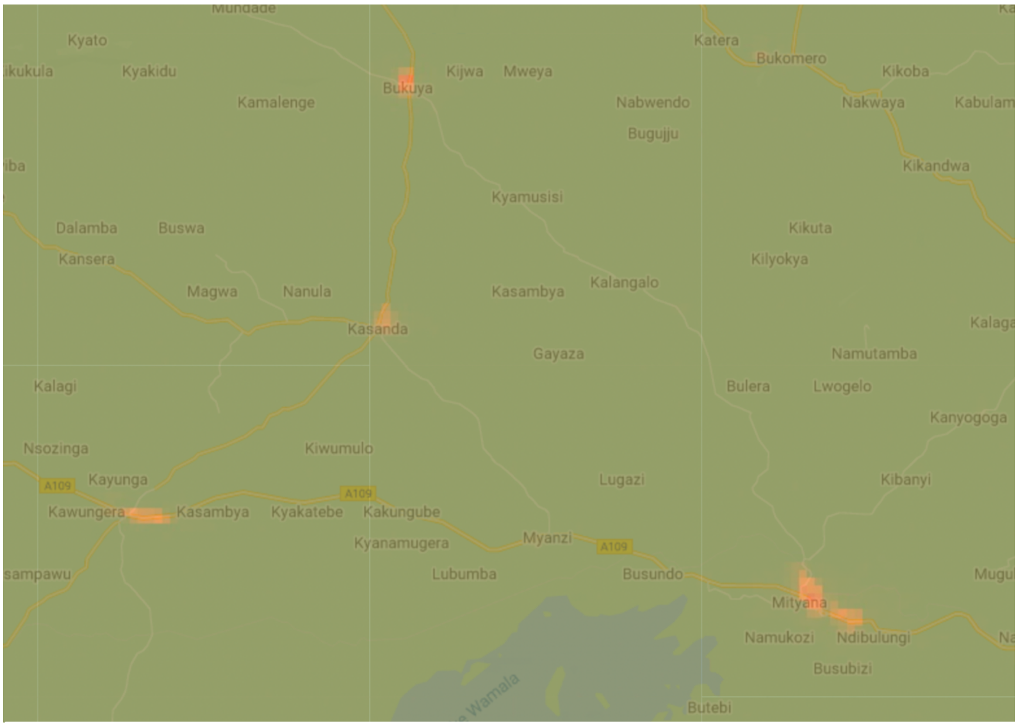


Figure 7. *Rate of change map centered due west of Kampala, just north of Lake Wamala.*

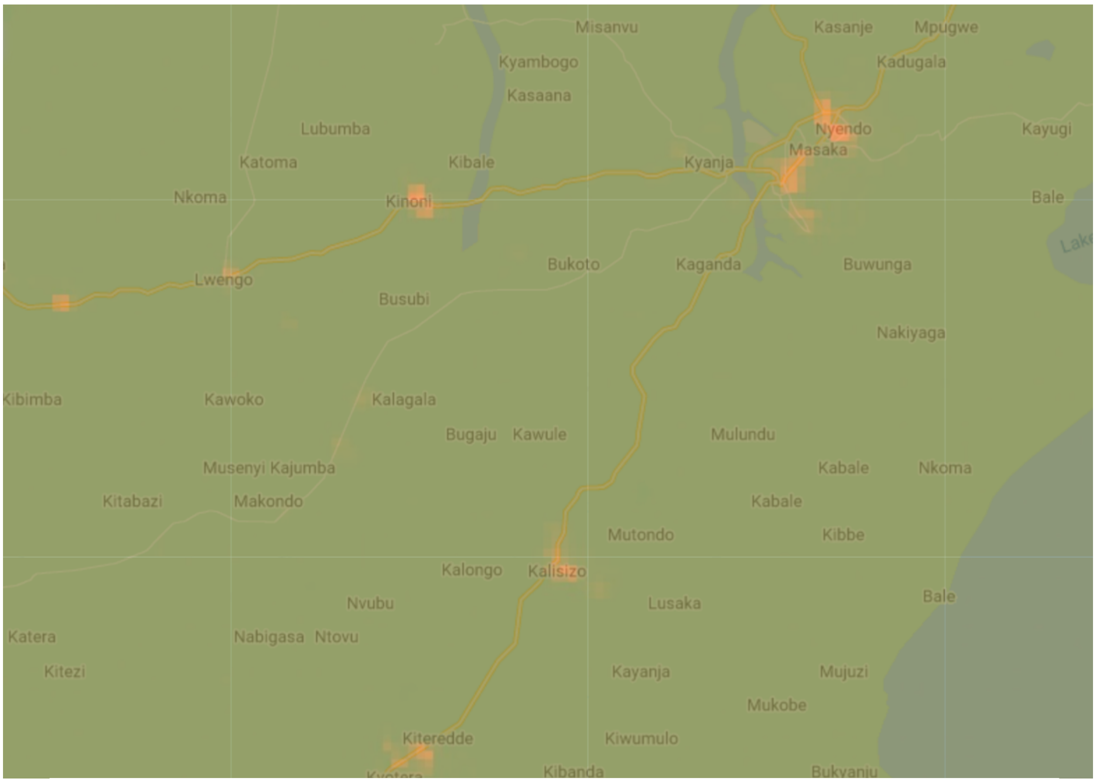


Figure 8. *Rate of change map located southwest of Kampala. Upper highway eventually leading to Rwanda and lower highway leading to Tanzania (both marked yellow).*

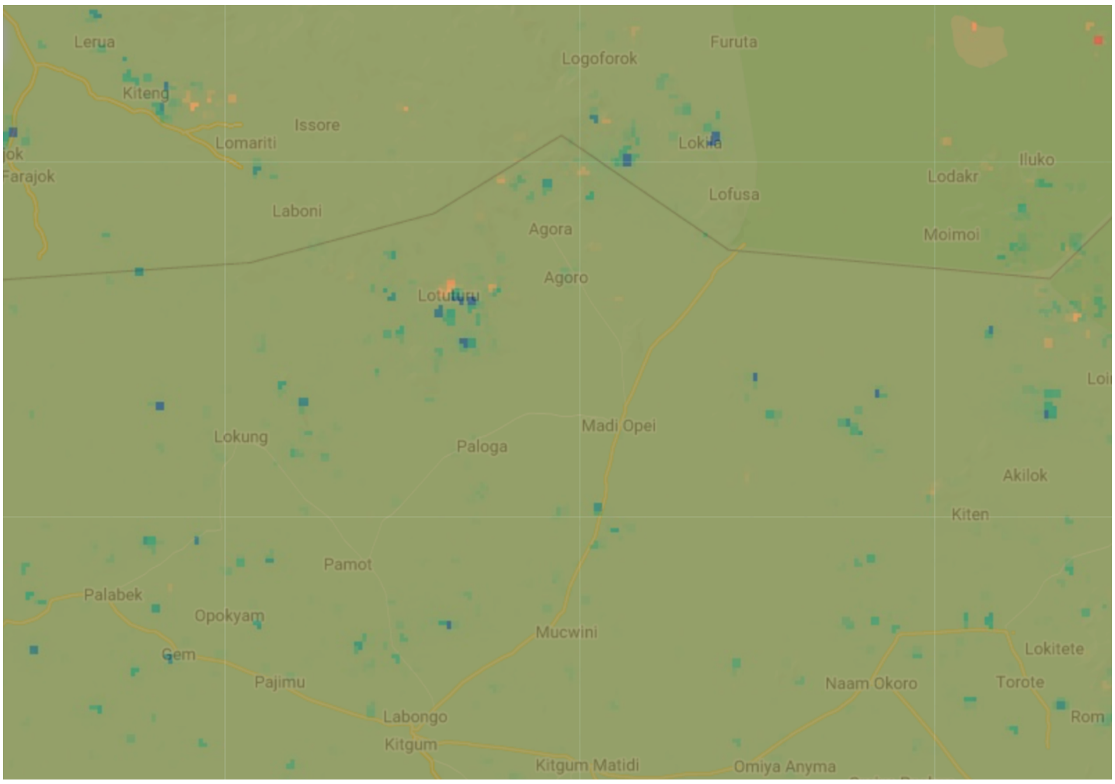


Figure 9. *Rate of change map located just south of the Uganda-South Sudan border. The uppermost section of the figure shows the South Sudanese side of the border.*

Beginning with the capital city Kampala, seen in *Figure 6,* one can see that there has been a positive rate of change in the SOL concentrated in the centre of the city, as well as in many of the towns along the major road networks leading out of the capital. In fact, there appears to have been a greater change in the SOL in many of these towns than in areas of central Kampala, implying that the greater part of economic activity, development and growth in the area is occurring along the outskirts of the city.

Continuing west – southwest along some of the major road networks leading from Kampala toward Tanzania, Rwanda, and the Democratic Republic of the Congo (DRC), one can see the positive rate of change in the SOL for many of the towns and cities located along these roads, with the larger part of growth occurring in towns and cities where two or more major roads intersect, as seen in *Figure 7 & 8.* A large portion of the positive change in SOL in Uganda appears to be concentrated around these road networks leading west - southwest, implying that much of the nation's growth, economic activity and development is occurring along the transportation corridors leading to Uganda's western and southern neighbours.

Conversely, the tremendous decrease in the SOL for the many areas located near or along the border to South Sudan can be seen in *Figure 9.* As opposed to the border with Tanzania, Rwanda or the DRI, this area has been ravaged by conflict since 2013[23], and the devastating effects of an active conflict on economic activity, health and development can be seen clearly via the associated decrease in the SOL in most settlements located on both sides of the border.

Although these examples only cover small portions of the entire country of Uganda, they can be seen as examples of the information such a map provides. Building on the results found at the national level indicating strong connections between the SOL and economic output, health status, and standard of living, this map allows the viewer to see where change in these areas has occurred. With the examples presented above, and results found at the national level, this map has been used to identify specific sub-national locations where positive change in the SOL and associated indicators has occurred, as well as locations where negative change has occurred as the result of an ongoing conflict.

[23] Source: https://www.accord.org.za/conflict-trends/south-sudan-uganda-relations/

7. DISCUSSION

This section will examine the findings of both the national and sub-national level analysis in relation to the literature presented earlier, and in relation to the goals of this paper. Thereafter the potential limitations of this paper's analysis will be briefly presented and discussed, before outlining methods of building on or improving upon this analysis in the future.

7.1 National level

As stated earlier, the purpose of the national level analysis was to investigate the relationship between night-time lights (measured as the SOL) and a selection of socioeconomic indicators in Uganda. The findings of the national level analysis support the existence of strong, and substantial relationships between the SOL and GDP, Life Expectancy, Infant Mortality Rate, Access to Electricity, and Urban Population. The existence of these relationships, and the values measured to determine their strength, speak in favour of the applicability of night-time lights measured by the VIIRS-DNB as an effective proxy for these indicators. Again, it is important to note that this paper does not claim the existence of a causal relationship between night-time lights and socioeconomic indicators, since the relationship can be argued to go both ways[24]. It is due to this problem of reverse causality that a causal statement regarding the nature of the relationship between night-time lights and socioeconomic indicators cannot be made. Instead, the ultimate goal of this analysis is to understand to which extent night-time lights can serve as a proxy for these indicators.

In relation to the findings of earlier studies presented in the Literature Review section, the findings of this paper's analysis have confirmed many of the earlier results. Although the national level analysis offers no predictions on future values due to a small sample size of only 7 measurements, the results of this analysis confirm previous findings presented in the Literature Review regarding the ability to measure urban population, GDP and correlated health indicators using night-time lights as a proxy. Additionally, this analysis finds a relationship between Access to Electricity and night-time lights that hasn't been presented in earlier literature, but based on the findings regarding other indicators, it is safe to assume that earlier studies would have found a similar relationship using the DMSP-OLS. However, although this paper finds relationships using new VIIRS-DNB data similar to those found

[24] For example, that increased economic output causes greater light emissions at night, or that increased light emissions at night indicate increasing economic activity, which in turn increases economic output.

using the DMSP-OLS, the relationships found in this paper cannot be classified as stronger or more precise than those found in earlier literature in terms of R or R^2 values. This is believed to be for a few reasons, firstly, the novelty of VIIRS-DNB data comes with the drawback that the amount of data available to conduct analysis on is far smaller than that of the DMSP-OLS, and it follows logically that a larger sample size can only benefit the accuracy of a linear regression. Furthermore, this paper conducted minimal pre-processing of the VIIRS-DNB data in comparison to the pre-processing conducted in many of the studies using the DMSP-OLS. Filtering out noise and cleaning data more effectively can offer great improvements to the results of the related analysis. With the vastly superior spatial resolution of the VIIRS-DNB shown in the Data section, one can assume that as more data becomes available, in combination with more detailed data pre-processing, results from similar studies using the VIIRS-DNB in the future should exceed those found using the DMSP-OLS.

To summarise, despite the relationships found in the national level analysis not being as strong as some of the results in earlier studies using the DMSP-OLS, it still confirms many of the findings of these earlier studies, and the analysis accomplishes its main goal of measuring the relationship between night-time lights and socioeconomic indicators. Furthermore, the results strongly support the conclusion that night-time lights, measured by the VIIRS-DNB, can be used as an effective proxy for the indicators investigated.

7.2 Sub-national level

By leaning on the results found on the national-level analysis, the map produced as the result of the sub-national level analysis allows the viewer to investigate and identify areas where a change in night-time lights, and by proxy the selected socioeconomic indicators, has occurred. As shown in the Results section, the viewer can find areas where the socioeconomic indicators have been impacted positively or negatively and get a sense of how rapid the change has been. The potential applications of such a map are many, for instance, in the hands of a humanitarian organization or non-governmental organization, this map would allow the monitoring of individual towns or neighbourhoods development, and thereby assist such organizations in identifying where their resources are best spent. Furthermore, being able to track the development of night-time lights on such a detailed scale would allow the user to follow the general effects of a small-scale and targeted policy or initiative. Through these potential applications, the rate of change map provides the beginning of a solution to combatting the issue of poor data quality greatly hindering economic research at the sub-national level in developing countries.

Although the map does not provide a numerical measurement for the development of night-time lights on a small scale, using it to identify specific areas of interest would allow the user in question to precisely measure night-time lights for the identified area with relative ease using an algorithm similar to the one used to produce the national level SOL by simply changing the specified boundary from Uganda to the area of interest. Access to such information would be especially useful in areas where being able to monitor development in person is difficult or even impossible, such as areas in active conflict. As shown in the sub-national results, this map allows for the identification of areas in a conflict zone that have been negatively impacted in terms of night-time lights, and by proxy socioeconomic indicators. Although this allows one to get a general sense of what areas have been most negatively impacted in terms of night-time lights, it is important to keep in mind that the development of night-time lights in a conflict zone may not be able to effectively serve as a proxy for other indicators. This since the amount of light emitted by night can be highly impacted by factors related directly to the conflict, such as blackouts, abandonment of settlements, and even the active choice of not having lights on at night to avoid standing out to potential threats.

In short, it is concluded that the sub-national analysis succeeds in its goal of building on national level relationships to identify precise locations where changes in socioeconomic indicators have taken place. Additionally, the sub-national analysis demonstrates the applicability of night-time lights as an alternative means of identifying and monitoring development on the sub-national level.

To summarise the results of both analyses, it is concluded that the national level analysis is successful in identifying and measuring substantial relationships between night-time lights and a selection of socioeconomic indicators, in addition to supporting the notion that night-time lights serve as an effective proxy for these indicators. The sub-national analysis explores and demonstrates the usefulness of night-time lights as a means of combatting difficulty in conducting sub-national research in developing countries, as well as the potential applications of VIIRS-DNB data in measuring and monitoring development on a sub-national level.

7.3 Limitations

Aside from some minor limitations mentioned throughout this paper[25] , there are a few main limitations associated with the analysis conducted and conclusions drawn in this paper that are important to keep in mind when evaluating the applicability of these results in practice, or when building upon these results in future research.

VIIRS-DNB

The first limitation concerns the VIIRS-DNB as a source of data itself. Despite the VIIRS-DNB representing a much-improved version of the DMSP-OLS sensor, there still exist three main limitations or challenges worth considering when using the VIIRS-DNB as a source of night-time light data. Firstly, as mentioned in the national level discussion, the VIIRS-DNB is still a fairly new sensor and as a result, algorithms for effectively pre-processing data or turning the raw nightly data into powerful research tool have not yet had time to fully develop. In this paper's case, an algorithm has been written in Python to source, pre-process and analyse VIIRS-DNB data itself, however, this implies that how well the data is pre-processed is dependent upon the programming level of the researcher. Furthermore, in order to replicate or build on the findings of this paper using the VIIRS-DNB, the researcher would have to be proficient in at least one programming language. In the future, there will hopefully be a wide range of analysis-ready VIIRS-DNB night-time light products available to the research community, which would serve to increase accessibility to such a powerful source of information.

Secondly, although it is considered a vast improvement over the DMSP-OLS, the VIIRS-DNB was still, like the DMSP-OLS, designed to be a weather satellite. With low-light imaging intended for the detection of moonlit clouds rather than night-time lights, the band used to capture images can include wavelengths that can't be seen by the human eye. One can hope that in the future, a satellite mission with the express purpose of imaging night-time lights will be launched[26] however, until then the VIIRS-DNB still represents the best option out there.

[25] Such as the choice of certain measurements being unsuitable for cross-country comparison, or the choice of "scale" when defining geographical boundaries greatly affecting results.
[26] Such as the one proposed by Elvidge et al (2007), in: "*The Nightsat mission concept*". https://doi.org/10.1080/01431160600981525

The final limitation or challenge associated with the VIIRS-DNB as a data source is its spatial resolution. Even though it is one of the primary improvements over the DMSP-OLS (Elvidge et al., 2013), the resolution of 742 x 742 metres is still quite large, especially when considering the sensors potential application in detecting very small human settlements or mapping urban dynamics at a small scale.

7.3.2 Agricultural land-use

Another limitation associated with using night-time lights as a proxy for socioeconomic indicators, especially in rural areas, is that the night-time lights measurement does not account for the positive effects of land being reserved for agricultural use, as these areas will normally remain dark during night. In practice, this means that agricultural land is interpreted as having no effect on socioeconomic indicators in rural areas, since it rarely contributes to the amount of light emitted at night. Although economic development can often be associated with the transition from an agriculture-based economy to an industrial one, the positive effects of agriculture, especially on a sub-national level, cannot be ignored. One potential method of accounting for these effects, similar to the framework used by Keola et al. (2015), would be to combine night-time light data with other sources of day-time satellite imagery data, however, this topic will be explored further in the Future Research section below.

7.3.3 Transferability to other countries

Finally, as pointed out by Ebener et al. (2005), it is important to keep in mind that although there appears to exist a significant relationship between night-time lights and socioeconomic indicators in developing countries, this relationship breaks down as a nation reaches higher levels of development. One could arrive at the same conclusion logically by considering that while the difference in night-time lights between for example Nairobi and Kampala can be assumed to reflect the difference in economic output, the same cannot be said for Stockholm and Copenhagen. After a certain level of development, the growth in night-time lights no longer seems to reflect the growth in the related socioeconomic indicators, and although the main application of night-time lights as a proxy is in the context of a developing country, it is important to keep the development status of a country in mind when conducting future research as the exact cut-off for this phenomenon is not well defined.

7.4 Future research

While writing this paper and conducting its analysis, a few topics were identified that while outside the scope of this paper, were deemed interesting as the subject of future analyses. This section will briefly touch upon some of these areas and propose potential methods of conducting future analysis to build and improve upon the one presented in this paper.

Firstly, as mentioned in the Limitations section above, night-time lights do not account for the positive effects of agricultural land use on socioeconomic indicators, nor the positive effects on the environment of reserving land for natural resource or biodiversity purposes. One potential method of incorporating these effects into the night-time lights measurement would be to in the future use a combination of satellite data sources to merge night-time lights data with land cover data that can identify land reserved for agriculture and forestry to investigate how well this merged data source measures socioeconomic indicators. Taking things one step further, one could potentially attempt to quantify the positive effects of agricultural land use on socioeconomic indicators using only land cover satellite data, and then combine this with night-time light data to estimate a "true" value of indicators based on these effects. To read more about such an approach, see the study conducted by Keola et al. (2015) found in the References section.

Secondly, when initially practicing working with nigh-time satellite data in Python and before deciding on Uganda as the subject of study for this paper, some basic linear regressions were conducted on the SOL and GDP in other countries in Sub Saharan Africa. Initially, it seemed that the slope regarding the effect of the log-SOL on GDP was very similar for both Kenya and Uganda, however this was not investigated further as the focus of this paper was to analyse a single country. In the future it would be worth conducting an analysis using night-time light measurements more suitable for cross-country comparison on several developing countries to determine if the relationship between the SOL and GDP, or even more socioeconomic indicators, could be generalized in a way that would allow for an effective estimation of these indicators in other developing nations lacking high quality economic data.

Finally, an area deemed important for future study is quantifying the relationship between night-time lights and socioeconomic indicators on a sub-national level. Slightly paradoxically, this would require access to high quality sub-national data for the country in question, which was unable to be acquired in this paper, and is one of the main issues in economic research that using night-time light aims to combat. However, it could be possible to produce a reliable sub-national dataset by carefully sourcing and combining various sub-national surveys and censuses. If one can find or produce a reliable dataset on the sub-national level for a developing country, it would be possible to investigate the relationship between night-time lights and socioeconomic indicators for individual administrative units in a country by performing an analysis similar to the one conducted on the national level in this paper. If done correctly, this would allow the researcher to effectively measure the effects that can be seen in the rate of change map produced in this paper, which would drastically improve upon its potential applications, as the ability to estimate and predict these effects could potentially replace the need for census or survey data in the future.

8. Conclusion

The objective of this paper was to evaluate how well night-time light data sourced from the VIIRS-DNB sensor can serve as a proxy for socioeconomic indicators in Uganda, in addition to investigating what improvements using VIIRS-DNB data can offer over the DMSP-OLS data that is more widely used in economic research. To achieve these goals, a series of linear regressions were conducted on a selection of socioeconomic indicators using the log of the calculated Sum of Lights measured by the VIIRS-DNB as the explanatory variable. Furthermore, a map of Uganda was constructed visualizing the rate of change of night-time lights at the same spatial resolution as the VIIRS-DNB sensor, allowing the viewer to explore where in the nation a change in night-time lights has occurred on a small scale.

This study concludes the existence of substantial relationships between night-time lights measured as the Sum of Lights in Uganda, and the indicators GDP, Life Expectancy, Infant Mortality Rate, Access to Electricity and Urban Population. The strength of these results indicate that night-time lights measured by the VIIRS-DNB can be used as a proxy to measure these indicators effectively and are in line with the results found in similar previous research using the DMSP-OLS. Additionally, the rate of change map illustrates the ability of the VIIRS-DNB to measure changes in night-time lights, and by proxy the chosen indicators, at a vastly higher spatial resolution than what has been previously possible using the DMSP-OLS.

However, before building on these results or applying them to a practical setting, there exist some limitations to the method used in this paper that are important to consider. This paper does not account for the effects of agriculture on the selected indicators which can produce inaccurate results, especially when studying agriculture-based developing economies. Furthermore, previous research has indicated that there exists a level of development above which the relationship between night-time lights and socioeconomic indicators breaks down, which must be kept in mind when applying this method to other countries. Lastly, despite the VIIRS-DNB being an improvement over the DMSP-OLS, it is not without its drawbacks, such as low volume of available data and low spatial resolution relative to what is required to effectively study urban dynamics at a small scale. Although this study comes with these associated limitations, the results still underline the applicability and usefulness of night-time lights as a method of measuring socioeconomic indicators in developing countries.

Finally, to further study the applicability of night-time lights measured by the VIIRS-DNB in economic research, future research could attempt to combine VIIRS-DNB data with other day-time satellite data sources to account for the effects of agriculture or forestry, which can result in stronger or more complete results. Additionally, future research could study the relationship between night-time lights and development in other developing nations, to potentially find a relationship that can be applied to any nation lacking high quality socioeconomic data. To build on the sub-national results produced in this paper, high-quality sub-national data could be sourced to investigate the relationship between night-time lights measured by the VIIRS-DNB and socioeconomic indicators at a much more detailed level than previously possible with the DMSP-OLS.

9. References

Doll, C. H., Muller, J. P., & Elvidge, C. D. (2000). Night-time Imagery as a Tool for Global Mapping of Socioeconomic Parameters and Greenhouse Gas Emissions. *AMBIO: A Journal of the Human Environment*, *29*(3), 157–162. https://doi.org/10.1579/0044-7447-29.3.157

Ebener, S. (2005). From wealth to health: modelling the distribution of income per capita at the sub-national level using night-time light imagery. *International Journal of Health Geographics*. https://ij-healthgeographics.biomedcentral.com/articles/10.1186/1476-072X-4-5

Elvidge, C. D., Baugh, K. E., Kihn, E. A., Kroehl, H. W., & Davis, E. R. (1997). Mapping city lights with nighttime data from the DMSP Operational Linescan System. *Photogrammetric Engineering and Remote Sensing*, *63*(6), 727-734.

Elvidge, C. D., Cinzano, P., Pettit, D. R., Arvesen, J., Sutton, P., Small, C., Nemani, R., Longcore, T., Rich, C., Safran, J., Weeks, J., & Ebener, S. (2007). The Nightsat mission concept. *International Journal of Remote Sensing*, *28*(12), 2645–2670. https://doi.org/10.1080/01431160600981525

Elvidge, C. D., Baugh, K. E., Zhizhin, M., & Hsu, F. C. (2013). Why VIIRS data are superior to DMSP for mapping nighttime lights. *Proceedings of the Asia-Pacific Advanced Network*, *35*(0), 62. https://doi.org/10.7125/apan.35

Ghosh, T., L Powell, R., D Elvidge, C., E Baugh, K., C Sutton, P., & Anderson, S. (2010). Shedding light on the global distribution of economic activity. *The Open Geography Journal*, *3*(1).

Gibson, J., Olivia, S., Boe-Gibson, G., & Li, C. (2021). Which night lights data should we use in economics, and where? *Journal of Development Economics*, *149*, 102602. https://doi.org/10.1016/j.jdeveco.2020.102602

Henderson, J. V., Storeygard, A., & Weil, D. N. (2012). Measuring Economic Growth from Outer Space. *American Economic Review*, *102*(2), 994–1028. https://doi.org/10.1257/aer.102.2.994

Keola, S., Andersson, M., & Hall, O. (2015). Monitoring Economic Development from Space: Using Nighttime Light and Land Cover Data to Measure Economic Growth. *World Development*, *66*, 322–334. https://doi.org/10.1016/j.worlddev.2014.08.017

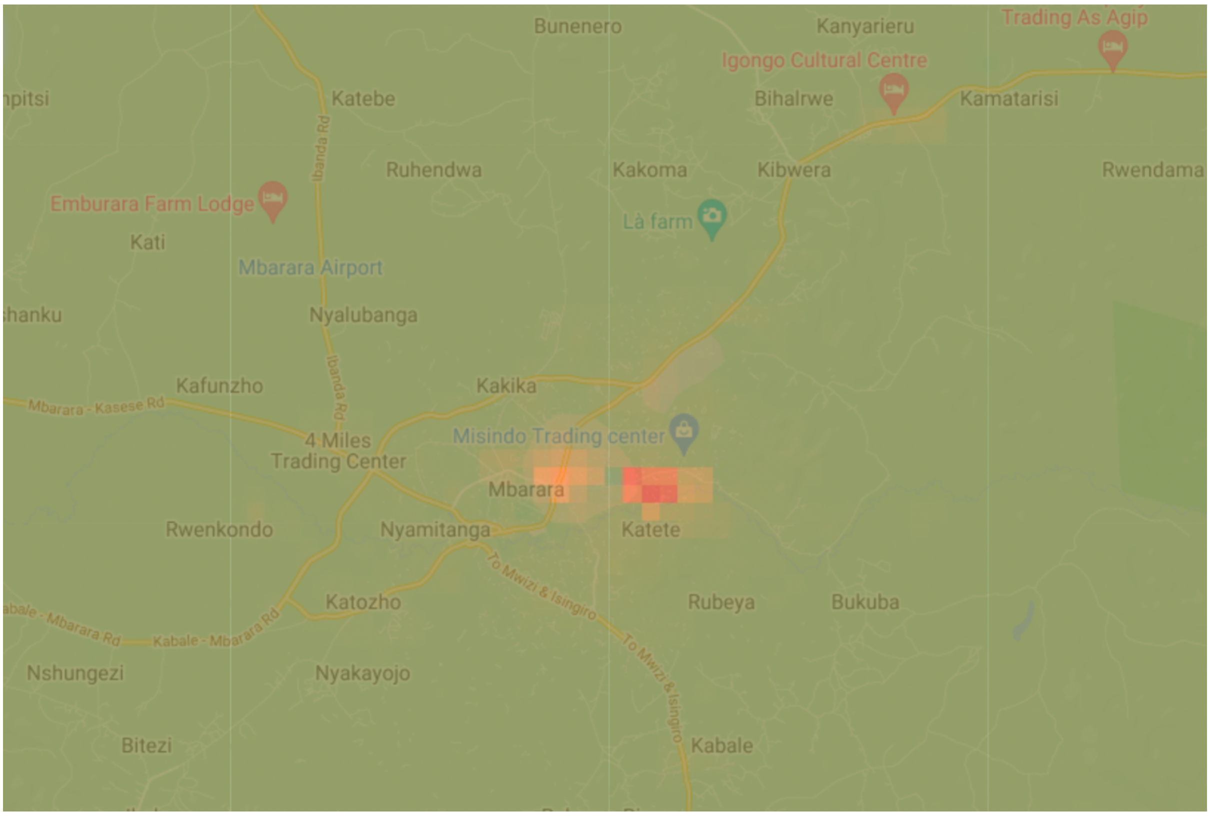
Nordhaus, W., & Chen, X. (2014). A sharper image? Estimates of the precision of nighttime lights as a proxy for economic statistics. *Journal of Economic Geography*, *15*(1), 217–246. https://doi.org/10.1093/jeg/lbu010

Sutton, P. C., & Costanza, R. (2002). Global estimates of market and non-market values derived from nighttime satellite imagery, land cover, and ecosystem service valuation. *Ecological Economics*, *41*(3), 509–527. https://doi.org/10.1016/s0921-8009(02)00097-6

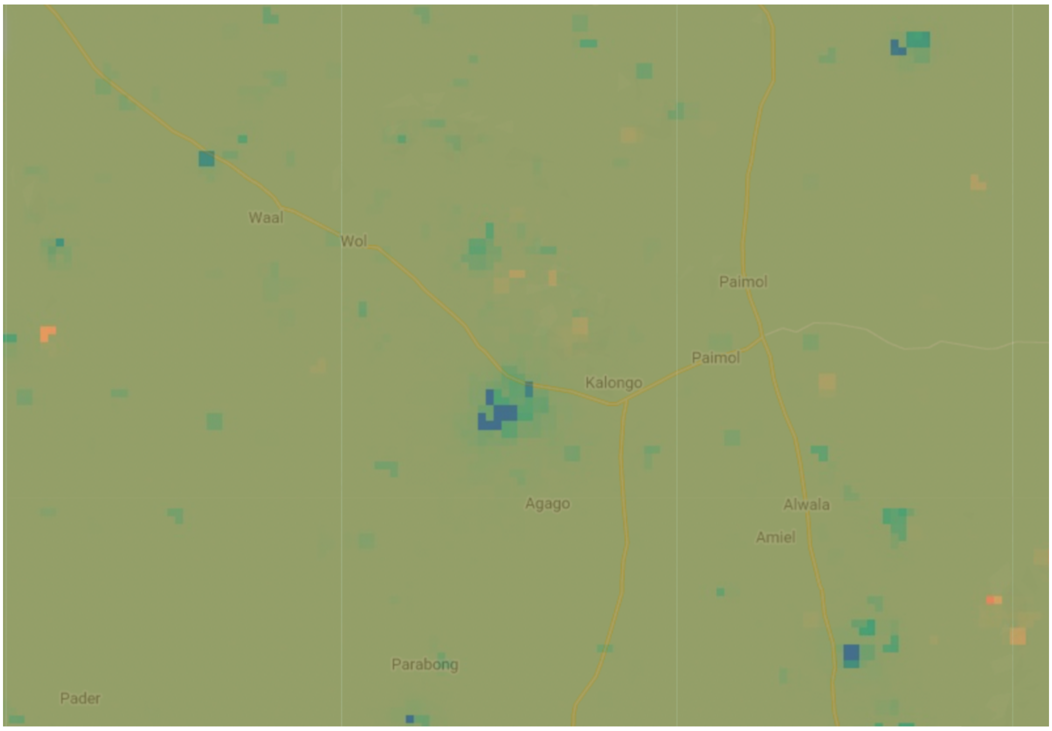
10. Appendix

Year	SOL
2014	56527,9502
2015	113804,9107
2016	68995,85675
2017	263997,6307
2018	248518,7168
2019	209950,0331
2020	274223,6422

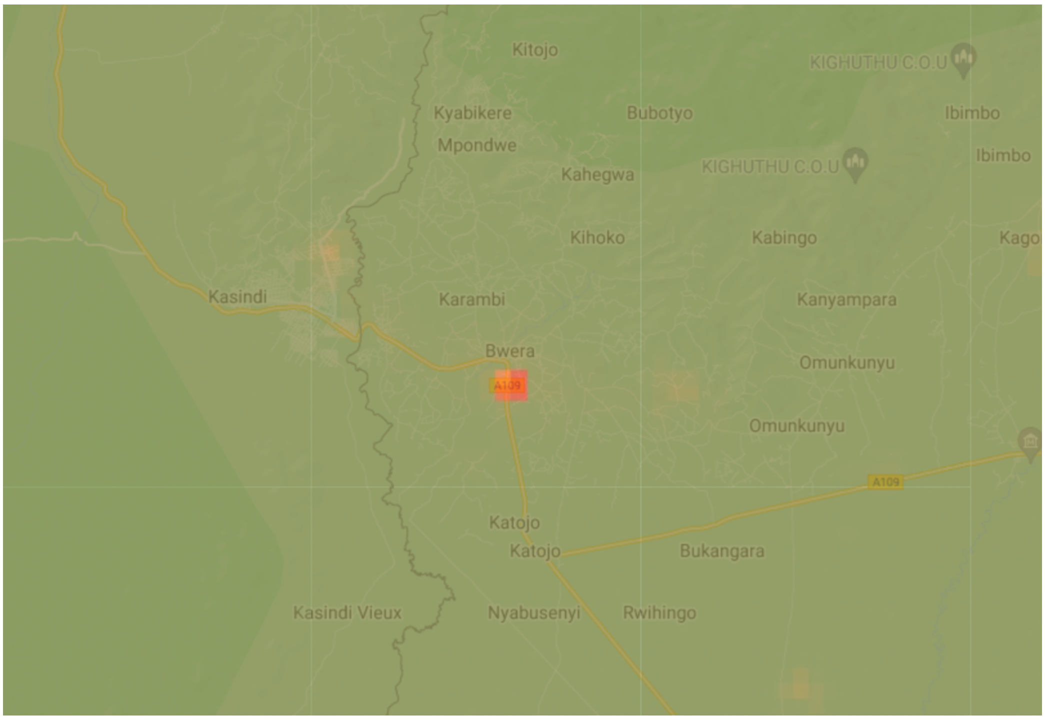
Appendix 1. *Yearly SOL time series produced in Python.*



Appendix 2. *Rate of change map centered on Mbarara, southwestern Uganda.*



Appendix 3. *Rate of change map centered on Kalongo, northern Uganda.*



Appendix 4. *Rate of change map centered on Bwera, situated east of the border to the DRC.*