Population, Demography and Nighttime Lights

An examination of the effects of population decline on settlement patterns in Europe

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Abstract: Nighttime satellite photographs of Earth reveal the location of lighting and provide a unique and highly accurate view of human settlement, density and distribution. Nighttime lights have been shown to correlate with economic development and population worldwide. Little research has been done on the link between nighttime lights and population change over time. This link is explored here for Europe between the period of 1992 and 2012 using GIS and regression analysis. This thesis examines whether population change, and specifically population decline, is reflected in nighttime lights or whether other demographic developments which have accompanied population decline in Europe are better reflected in nighttime lights. The results suggest that population decline in Europe is not coupled with decline in nighttime lights. Demographic and structural changes consistent with population decline in Europe may contribute to the divergence between population and nighttime lights. The age structure of the population and the GDP show correlation with lighting during periods of growing and declining population. These results suggest that human settlement distribution in Europe is more closely related to the age structure of the population and to GDP than to the size of the population and that declining populations will not lead to reductions in the human footprint on Earth.

Key words: nighttime lights, demographic transition, population decline, human settlement distribution

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List of Abbreviations

CIESIN	Center for International Earth Science Information Network
DMSP-OLS	Defense Meteorological Satellite Program's Operational Linescan System
DN	Digital Number
ECHP	European Community Household Panel
EU-SILC	European Statistics on Income and Living Conditions
FUR	Functional Urban Area
GDP	Gross Domestic Product
GPW	Gridded Population of the World
GRP	Gross Regional Product
GSP	Gross State Product
IEA	International Energy Agency
ISA	Impervious Surface Area
NOAA-NGDC	National Oceanic and Atmospheric Association's National Geophysical Data Center
PMT	Photomultiplier Tube
SDT	Second Demographic Transition
SOL	Sum of Lights
TFR	Total Fertility Rate
UN DESA	United Nations Department of Economic and Social Affairs
USD	US Dollars
USGS	U.S. Geological Survey

Country Name Abbreviations

ALB	Albania	ITA	Italy
AUT	Austria	LIE	Liechtenstein
BEL	Belgium	LTU	Lithuania
BGR	Bulgaria	LUX	Luxembourg
BIH	Bosnia and Herzegovina	LVA	Latvia
BLR	Belarus	MDA	Moldova
CHE	Switzerland	MKD	Macedonia, FYR
CZE	Czech Republic	MLT	Malta
DEU	Germany	MNE	Montenegro
DNK	Denmark	NLD	Netherlands
ESP	Spain	POL	Poland
EST	Estonia	PRT	Portugal
FRA	France	ROU	Romania
GBR	United Kingdom	SRB	Serbia
GRC	Greece	SVK	Slovakia
HRV	Croatia	SVN	Slovenia
HUN	Hungary	UKR	Ukraine
IRL	Ireland		

Chapter 1: Introduction

1.1 Background

Today, most places where humans have settled employ artificial lighting to some extent. One can imagine the amount of light that major urban locations such as Times Square or the Las Vegas Strip in the United States or Tokyo, Japan's major downtown districts generate. However, even remote rural villages in the most developing countries have limited access to artificial lighting as well. In fact, according to the International Energy Agency (IEA) World Energy Outlook (2011), 94 percent of urban areas and 68 percent of rural areas globally were electrified in 2009. Nighttime offers the dark conditions necessary to observe lighting clearly and, if one looks down from space at night, one gets a clear sense of the settlement patterns of humans on Earth, as seen in Figure 1. One can trace the shape of the continents and differentiate between areas of dense development, sparse development and no development at all. Moving in closer, one can begin to pick out major cities, satellite towns and transportation networks. If one returns to examine the same location year after year, one can track the changes in development over time. New developments appear as new clusters of lights and urban sprawl can be discovered in clusters whose size magnifies over time. Expanding transportation connections between two cities materialize as a new linear pattern of lights. Downturns in development are also reflected in lighting from year to year. Abandoned settlements cease to be lit and no longer appear to the viewer observing from space. The distribution of lighting on Earth, best observed from space at night, therefore provides a unique and highly accurate view of human settlement, density and distribution (Levin and Duke, 2012; Chen and Nordhaus, 2011).

Such observations of lighting at night are known as nighttime lights imagery and are gathered by satellites that photograph the Earth at night. This technique is known as remote sensing, which is generally defined as gathering information about objects from a distance without making physical contact. Nighttime lights data are the only remotely sensed dataset that is directly related to human development activity. There are other sources of remotely sensed data that can be used to identify and examine human settlement on Earth; however, they must be manipulated and interpreted in order to reveal information regarding the distribution of human settlement which introduces a level of uncertainty and subjectivity into analysis that is not present when using nighttime lights data since artificial lighting is directly related to human settlement.

Figure 1. Global nighttime lights
Source: NASA, 2012

The superiority of nighttime lights data when it comes to identifying human settlement patterns may be one reason why they have begun to be used within social science research. A second is the fact that nighttime lights data has global coverage and can be freely accessed for the period between 1992 and 2012, meaning that it can be applied in a wide range of geographic and temporal situations. It is no surprise, then, that within the social sciences, observations of lighting at night are used to better understand the spatial distribution of human settlement and that datasets of such observations have been used in research related to economic development[1], population[2], urbanisation[3], epidemiology[4], wars and crime[5] and poverty[6].

1.2 Research Rationale

Nighttime lights have more specifically been used as a proxy for socio-economic variables, most frequently population and income (Levin and Duke, 2012). The use of nighttime lights data is especially popular in estimating such variables in countries and regions where traditional economic and demographic data is not available or where it is thought to be inaccurate. Generally, studies employing nighttime lights as proxies for economic development and population are undertaken for one study year. A good body of knowledge exists regarding the effectiveness of nighttime lights as proxies for economic and demographic data during a snapshot of time. However, very few studies take advantage of the full temporal extent of the data available. Therefore, a clear research gap exists for findings on the change in nighttime lighting over time and how this may or may not be linked with economic development and population.

This thesis aims to contribute to minimizing this identified research gap. In order to narrow down the scope of the research, Europe was selected as the study area. This decision was made because Europe tends to be a data rich region, meaning that comparisons between nighttime lights and other variables should be more accurate than in regions with poorer statistical data. Having selected Europe as the study area, the decision was made to specifically study population change in relation to nighttime lights. Population change is an interesting study at a time when Europe's population growth is slowing and when its population will soon begin to decline (United Nations Department of Economic and Social Affairs (UN DESA), 2013a). Along with this population decline, which has been caused by steadily decreasing fertility rates, come other demographic changes such as an altering age structure and changes to traditional household composition. These demographic developments are together referred to as the Second Demographic Transition (SDT) and may also play a role in lighting change.

1.3 Research Questions

Acknowledging the emerging patterns of population decline and associated demographic changes in Europe, it becomes relevant to determine the following:

- How population and nighttime lights have changed between 1992 and 2012

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[1] See, for example: Henderson, Storeygard and Weil, 2012; Chen and Nordhaus, 2011; Ghosh, et al., 2010; Doll, Muller and Morley, 2006; Elvidge, et al., 1997
[2] See, for example: Doll, 2010a; Pozzi, Small and Yetman, 2002; Sutton, et al., 2001; Elvidge, et al., 1997; Sutton, et al., 1997; Sutton, 1997
[3] See, for example: Elvidge, et al., 2007; Small, Pozzi and Elvidge, 2005; Henderson, et al., 2003; Imhoff, et al., 1997
[4] See, for example: Bharti, et al., 2011; Kloog, et al., 2008
[5] See, for example: Witmer and O'Loughlin, 2011; Agnew, et al., 2008
[6] See, for example: Doll and Pachauri, 2010; Elvidge, et al., 2009a; Moor, et al., 2008

- If there is a relationship between population and nighttime lights in general and whether population change and specifically population decline are reflected in nighttime lights
- If other demographic developments which have accompanied population decline in Europe are related to nighttime lights

1.4 Methodological Considerations

A time series exploration of the intersection between population change and change in nighttime lights in Europe, undertaken through country-level change and regression analysis, is the focus of this thesis. Geographic Information Systems (GIS) and statistical analysis packages were the central methodological tools used in this analysis. Quantitative research methods were selected over qualitative research methods as a direct result of the research questions being posed, which were developed based on the chosen direction of study, that is, the desire to employ nighttime lights imagery within a study of population change in Europe.

Employing nighttime lights imagery lends itself to a more quantitatively focused study, as was made clear by a review of the relevant nighttime lights literature. Additionally, quantitative research methods can be more easily generalized and abstracted to other temporal and spatial scales and locations, which is a major goal of this research. The methods of this thesis, while specifically applied to Europe, should be translatable to other geographic regions and reproducible in the future. Furthermore, the quantitative methods employed in this study are more objective than qualitative research methods tend to be. The use of remotely sensed data as an indicator of human settlement patterns in Europe eliminates subjective indicators of development patterns such as urban population surveys and country-level differences in data collection methods, although such differences are still present in the demographic data employed in this study.

1.5 Research Structure

This thesis is divided into five chapters. This introduction is followed by the second chapter which is dedicated to establishing the theoretical framework for the research. First, a review of nighttime lights studies is provided in order to further elucidate the identified research gap and to establish common analysis methods relevant to the use of nighttime lights within social science studies and specifically population studies. Second, a review of the theoretical background behind European population change over time is provided in order to establish a basis from which to draw hypotheses. The third chapter is dedicated to an overview of the datasets and data collection methods employed in the study, with a focus on the nighttime lights dataset. The fourth chapter sets out the results of the study. Finally, the fifth chapter provides a discussion of the relevant findings and sets out brief conclusions along with directions for future study.

1.6 Summary of Results

The results of this thesis suggest that population decline in Europe is not coupled with decline in nighttime lights. Instead, change in nighttime lights is engrained in each country's development path regardless of a reversal in population growth. Whereas population declined throughout the study period in Eastern Europe and also in some countries in Western Europe, both lighted area and intensity showed an overall tendency for growth. While the correlations between population and lighting over time during periods of population decline were negative, there is promising evidence that demographic changes consistent with population decline may have contributed to the divergence between population and nighttime lights. The age structure of the population and the gross domestic product (GDP) in particular had moderate to strong correlations with lighting that remained consistent both during periods of population decline and increase, suggesting that such factors could contribute to continuous growth in lighting despite population decline. Despite strong correlation between population and lighting on a year by year basis, on a time series basis, the positive association between lighting and population broke down when population declined and it appears that other demographic characteristics of the SDT as well as economic development contributed to this breakdown by requiring increased land use despite decreasing populations.

Chapter 2: Theoretical Framework

This section sets out the theoretical boundaries for this thesis. It begins with a review of existing applications of the nighttime lights dataset within the discipline of social sciences, ending with a specific look at studies related to population. This was done in an effort to identify both research gaps and effective analysis methods. The section then moves on to expand the theoretical framework past population and nighttime lights to include demographic theories behind population change in Europe. The intersection between nighttime light theories and European demographic change theories forms the theoretical boundaries of this thesis from within which the previously identified research questions are advanced.

2.1 Nighttime Lights Applications

The use of remote sensing within social science research is rare (Hall, 2010). Nighttime lights are no exception to this, despite the fact that their potential to be used as an inventory for human settlement was identified in the 1980s (Elvidge, et al., 1997). Nonetheless, hundreds of articles relating to nighttime lights were identified through a search of online journal article databases. Based on their titles, these were grouped into either social science or natural science applications. Those publications deemed to relate to the social sciences were examined more closely and three themes were selected for further study: economic activity, urban extent and population. These were selected because they appeared most frequently within the identified literature and because they were most relevant to the topic of interest. This section will now present a review of publications within the three themes. It concludes with a summary table which illustrates the research gaps and methodologies.

2.1.1 Economic Activity

One of the central uses of the nighttime lights dataset is as a measure of and proxy for economic activity. The relationship between economic activity and light has been explored by several authors and all have concluded that there is indeed a positive relationship between the light emitted and the level of economic development within a region. This understanding has been used to estimate both GDP and economic growth.

An early identification of the strength of the relationship between nighttime lights and economic development was made by Elvidge, et al. (1997), who explored the relationship between lighted area and GDP, population and electrical power consumption in the countries of South America, the United States, Madagascar and several island nations of the Caribbean and the Indian Ocean. Using simple linear regression over a single year (1994/1995) they found that GDP exhibits a strong linear relationship with the lighted area ($R^2 = 0.97$).

Elvidge, et al.'s (1997) publication is unique in that it deals with the relationship between economic activity and lighted area. Most other publications related to economic activity examine its relationship with light intensity. Doll, Muller and Morley (2006) were one of the first to apply this relationship to estimating economic activity on a national and sub-national basis. They identified the unique linear relationships between gross regional product (GRP) and lighting for the European Union and the United States using 1996/1997 data and found that one linear relationship was not appropriate since some cities were outliers. With these outliers removed, they were able to generate simple linear regressions for each country, with R^2 values ranging from 0.85 to 0.98, and used these to generate a gridded map which estimated GRP at the 5 km level.

Building on this research, Ghosh, et al. (2010) generated a global disaggregated map of economic activity with a spatial resolution of 30 arc seconds (approximately 1 km^2 at the equator). They first performed a linear regression between gross state product (GSP), GDP and light intensity for 2006 for various administrative units in the states of China, India, Mexico and the United States to obtain an estimate of total economic activity for each administrative unit. These values were then spatially distributed within a global grid using the percent contribution of agriculture towards GDP, a population grid and the nighttime lights image. Ghosh, et al. (2010) improved on Doll, Muller and Morley (2006) through the use of the population grid and the percent contribution of agriculture as they were able to assign economic activity to agricultural areas which generate economic activity but which are not usually captured by the nighttime lights dataset since they are not often lit.

Chen and Nordhaus (2011) were one of the first to analyze the relationship between economic activity and light using a time series approach. Their aim was to identify how much light intensity could contribute in estimating true GDP measures. They accomplished this by calculating the weights for light intensity that would reduce the mean squared error for the difference between the true GDP values and the estimated ones in all countries globally for 1992 to 2008. They found that light intensity has a high potential to add value to GDP estimation in data-poor countries, both at the national and sub-national level. In data rich countries, light intensity data does not add as much value because its measurement error is generally higher than that of the available economic data.

One of the most recent applications of the nighttime lights dataset in relation to economic activity was by Henderson, Storeygard and Weil (2012). Rather than exploring the relationship of lights with GDP, they explored the relationship with economic growth. Like Chen and Nordhaus (2011), they performed an analysis over a time series for the period between 1992 and 2008. They developed a statistical model which estimated GDP growth using country specific economic data combined with light intensity values. Similar to Chen and Nordhaus (2011), they applied different weights for the lighting data and existing economic data based on the quality of the economic data. They found that for “bad” data countries there are often large differences (both positive and negative) between the recorded economic growth and the estimated growth. They also found that their model tended to underestimate economic growth in countries with low growth and overestimate it in countries with high growth.

All in all, the literature confirms that there is a strong relationship between nighttime lights and economic activity, both in terms of lighted area and intensity and in terms of GDP and GDP growth. Most studies have tended to be for single years, although two time-series studies were also discovered. Likewise, light intensity has been used more commonly than lighted area in analyses related to economic activity. Linear regression is the most common method used to establish and analyse relationships within this theme.

2.1.2 Urban Extent

Another application of nighttime lights in the social sciences has been in determining or validating urban extent. This is relevant for two reasons. First, administrative boundaries for cities do not accurately depict their built up urban area and having more accurate information regarding the actual shape and size of cities is beneficial in many applications. Second, nighttime lights data often overestimate the spatial extent of development due to a phenomenon known as blooming (covered in Section 3.3.1). The studies that have been undertaken on urban extent aim to reduce this overestimation of the lighted area and provide accurate estimates of urban boundaries.

Imhoff, et al. (1997) produced one of the first studies dealing with urban extent. They used the 1994/1995 nighttime lights dataset for the percentage of lighted observations to accurately map the urban area for the United States by finding the optimal threshold at which contiguous polygons shrank in area but before which they started to fragment. The result eliminated small and poorly lit inhabited areas and showed no statistically significant difference to census generated results of urban area.

A similar study was undertaken by Henderson, et al. (2003) for three economically diverse cities: Lhasa, Tibet; Beijing, China and San Francisco, United States. They compared two nighttime lights datasets (percent lighted observations from 1994/1995 and radiance calibrated from 1996/1997) with Landsat land cover imagery to find thresholds which most accurately approximated the urban extent as determined from the Landsat imagery. They found that there is no universal threshold which can be applied to identify urban boundaries; very different thresholds are required for cities with different levels of development.

Small, Pozzi and Elvidge (2005) also examined differing thresholds by evaluating the results of changing thresholds for three different years (1992/1993, 1994/1995 and 2000). They confirmed that increasing the thresholds leads to fragmentation and reduction of the contiguous lighted area. They also found that smaller lighted areas are detected less frequently than larger areas and that larger areas have more convoluted shapes than smaller areas. They concluded that thresholds above 90 percent lead to the closest matches in urban area between nighttime light and Landsat datasets; however, just as Henderson, et al. (2003), they found that there is no single threshold.

Elvidge, et al. (2007) took a different approach to determining urban extent by instead producing the first global grid of impervious surface area (ISA) density. They used nighttime lights and gridded population data along with an existing U.S. Geological Survey (USGS) ISA dataset as a reference dataset to develop a linear regression model to estimate the density of ISA in the United States which was then applied to generate the global gridded ISA density map. They found that their calculations were slightly higher than the USGS calculations for ISA in the United States.

In summary, the nighttime lights dataset has been used to develop estimates of global and local urban extent. Both light intensity and percent lighted observations have been used to develop thresholds at which urban areas are best represented; however, most studies are clear that a universal threshold is not appropriate. Studies related to urban extent have focused exclusively on single year analyses. From the publications analysed, no work has been done on examining the urban extent over a time series.

2.1.3 Population

A final important application of the nighttime lights dataset is in studies related to population. Here the dataset has been employed with general population levels as well as with population density and distribution.

Elvidge, et al.'s (1997) study, introduced in Section 2.1.1, also addressed the relationship between lighted area and total population. Here, they again found a strong linear relationship (R^2=0.85), although it was weaker than the relationship they found with GDP. The authors also identified a pronounced regional influence on the relationship, with countries with poorly developed economies lying as outliers from the standard linear relationship. They suggested that national or regional calibrations of the linear model might improve the strength of the relationship.

Unlike in the publications related to economic activity, lighted area is a more common measure within publications related to population. In fact, Sutton, et al. (1997) found that there is no strong correlation between population density and the light intensity level of individual pixels in the United States. They attributed this to the fact that light intensity values saturate in urban centres, where most of the variation in population density occurs (see Section 3.3.1 for an explanation of saturation). However, they found a strong linear correlation between the area of lighted clusters and population density ($R^2 = 0.62$). They found that a regression model using this relationship is capable of detecting places with low population densities; however, it underestimates the population density of urban centres and overestimates that of suburban areas.

Sutton (1997) used the relationships identified by Sutton, et al. (1997) to model population density within urban clusters in the United States. He identified clusters of continuously lit pixels and calculated the shortest distance to the edge of the cluster for each lighted pixel. Then, using known population data for cities associated with each cluster he assigned the population density at each pixel based on the relationship between the distance to the edge of the cluster and the total population. This relationship was based on several decay functions, including linear, parabolic, exponential and Gaussian as well as an empirical decay function estimated from actual population density data. He found that the model only accounts for 25 percent of the variation in population density of urban areas. However, he stated that the low R^2 is to be expected because of the model's inability to identify population density at constant distance from cluster edges and that the model may still be a good basis for creating a model to estimate population density in areas where good population data is unavailable.

This model was further expanded in Sutton, et al. (2001). They aimed to estimate population totals rather than population density and apply it on a global scale. They applied thresholds to identify urban areas and then, using known urban populations, developed a linear regression model between the area of each urban region and its population. Using this model, they estimated the population for all urban areas within each country and then calculated the total population using data on the percentage of the population that lives in urban areas. They also disaggregated the global population into three groups based on their income level and found that the strength of the relationship between the size of an urban area and its population is increased when disaggregated.

Doll (2010a) conducted a study to examine the likelihood of a pixel appearing lit at a given population density in order to describe how light detection varies with population density. He tested two population datasets against the stable lights dataset for 2000 and 2008 for developed and developing regions. He found that developed regions have fewer unlit cells at all population densities and that they increase sharply in brightness with relatively small increases in population density, while less developed regions show more gradual increases. Finally, he found that globally, at 2000 persons/km^2, approximately 15 percent of the population is undetected by light emissions; however, in OECD areas basically all but the lowest population densities are detectable by light.

Apart from being used to explore population density and population totals, nighttime lights have also been used to examine population distribution. Pozzi, Small and Yetman (2002) produced a population distribution dataset as an attempt to improve on the Gridded Population of the World (GPW) dataset available from the Center for International Earth Science Information Network (CIESIN). They first examined the relationship between the population and the percentage frequency of light in the Northeastern United States, France, Spain and Portugal. They then developed a transfer function to map the light frequency into population density and generated an algorithm to relocate population from areas where the population density was lower than a threshold to lighted areas. They found that in countries with large populations but poor spatial detail in their population estimates their model improved on the GPW dataset.

In summary, the literature displays evidence of a strong relationship between nighttime lights and population. As with studies related to economic activity, the studies related to population focused on single year analysis. In fact, none of the publications examined dealt with multi-year analysis. Contrary to the trend in studies related to economic activity, those related to population focus more on the relationship with lighted area than on the relationship with lighting intensity. Finally, linear regression is also a common method within population related studies.

Table 1 summarizes the publications which were reviewed based on their methods and data used. In terms of population specifically, a strong relationship with the nighttime lights dataset has been established in the literature. Generally, lighted area is seen to have a strong linear relationship with population counts as well as population density and this relationship has been employed in developing pixel level accounts of population and population density worldwide. Despite the progress that has been made in using the nighttime lights dataset as a proxy for population and other socio-economic indicators such as GDP and urban development, there remain several research gaps that could be addressed.

Table 1. Nighttime lights publications' methodology and data sources

Publication	Theme *	Year	Light dataset product			Temporal Scale		Spatial scale		Location		Analysis focus	
			Stable lights	Radiance calibrated	% frequency light detection	Single year	Time series	Pixel level	Aggregated	Global	Local	Light intensity	Lighted area/light detection
Chen and Nordhaus, 2011	E	1992-1998	•				•	•		•		•	
Doll, 2010a	P	2000, 2008	•			•		•		•			•
Doll, Muller and Morley, 2006	E	1996/1997		•		•		•			•	•	
Elvidge, et al., 1997	E/P	1994/1995	•			•			•		•		•
Elvidge, et al., 2007	U	Not given		•		•		•		•		•	
Ghosh, et al., 2010	E	2006	•	•		•		•		•		•	
Henderson, et al., 2003	U	1994/1995, 1996/1997		•	•	•		•			•		•
Henderson, Storeygard and Weil, 2012	E	1992-1998	•				•		•	•		•	
Imhoff, et al., 1997	U	1994/1995			•	•		•			•		•
Pozzi, Small and Yetman, 2002	P	1994/1995	•			•		•		•			•
Small, Pozzi and Elvidge, 2005	U	1992/93, 1994/95, 2000			•	•		•		•			•
Sutton, et al., 1997	P	1994/1995	•			•		•			•	•	•
Sutton, et al., 2001	P	Not given			•	•			•	•			•
Sutton, 1997	P	1994/1995	•			•			•		•		•

* E = economic activity, P = population, U = urban extent

There were very few studies which took advantage of the full temporal range of the nighttime lights dataset. It was most common for studies to focus on one year to derive the relationship between nighttime lights and the variable of interest. This ignores the possibility that the relationship may change over time and become more or less significant. Therefore an opportunity exists to evaluate the changing relationship between nighttime lights and socio-economic indicators in order to determine whether changes in such indicators are reflected in nighttime lights or whether changes in nighttime lights occur independently from these indicators. This is important because if nighttime lights become uncoupled from socio-economic indicators over time then the key linear relationships that have been established in the literature as the basis for estimation of socio-economic indicators become less significant since they may only be applicable during certain periods of development.

Additionally, few studies employed both lighted area and light intensity as a measure of lighting. Lighting intensity and area each reflect a different component of human settlement patterns, mainly the intensity of development and the extent of development respectively. By undertaking analyses using both nighttime light indicators it is possible to comment on the difference between the two in terms of the strength of the relationship with socio-economic indicators and therefore on their ability to explain the changes and variation in such indicators.

Taking these opportunities for further research within the area of nighttime lights as a starting point, this thesis will take advantage of the full temporal scope of the nighttime lights dataset, which is available from 1992 to 2012, as well as both light intensity and lighted area as lighting indicators. The goal of the thesis is to use this time series to evaluate the effect of population change on nighttime lights. It specifically seeks to understand whether (or how) population decline is reflected in nighttime lights, and therefore, by proxy, in human settlement patterns. The following section aims to broaden the theoretical framework to include theories of population and development change in Europe. This expanded framework sets the boundaries from within which the relationship between nighttime lights and demographic change are later analysed.

2.2 Population Dynamics in Europe

While the 20th century was characterized by dramatic and sustained global population growth, this growth is expected to slow during the 21st century. During the 20th century, the world population increased from 1.6 billion to 6.1 billion (Clark, 2004). Today, it is estimated to be approximately 7.2 billion and is projected to have grown to 9.6 billion by 2050 and to a further 10.9 billion by 2100, according to the UN World Population Prospects (2012, medium variant) (UN DESA, 2013b). While absolute population growth is expected, growth rates are projected to drop from the current 1.2 percent to approximately 0.1 percent in 2100 (UN DESA, 2013a).

Population growth, however, is not a universal feature of the 21st century. Almost all of the projected growth until 2100 has been attributed to developing countries (UN DESA, 2013b). In contrast, the population of the more developed countries, which include all regions of Europe as well as North America, Australia, New Zealand and Japan, is expected to grow by a mere 25 million people by 2100, with most of this growth coming from immigration (UN DESA, 2013b). In fact, the rate of natural increase, which is the rate at which the population increases without migration, is expected to become negative in developed countries sometime between 2020 and 2030 (UN DESA, 2013a). The population of the more developed countries is expected to peak in approximately 2050 at 1.3 billion (UN DESA, 2013a).

In Europe specifically, population decline sets in approximately 25 years earlier, sometime between 2015 and 2020 (UN DESA, 2013a). Here, the rate of natural increase has been negative since approximately 2000 (UN DESA, 2013a). Therefore, only positive net migration has been driving population growth in Europe overall for the last decade. With negative rates of natural increase projected to decline further and immigration rates also projected to decline, it is clear that Europe has entered into a period where sustained population growth is no longer the case. Furthermore, the trends which have led to the end of population growth do not show signs of reversal. Therefore, it is expected that population decline is the new norm for Europe.

It is interesting and important to understand the factors which have driven Europe's demographic development up until the current period of decline as well as how human settlement patterns and population change have been linked in the past in Europe. With this understanding, it will then be important to develop an understanding of the factors which have contributed to the observed population decline. Following that, it will be possible to develop hypotheses about the effects of decline on nighttime lights.

2.2.1 The Demographic Transition

The demographic transition theory attempts to provide a universal explanation for the demographic trajectory of countries during modernization. It was first formalized by Warren Thompson in 1929 as an explanation for the trajectory of population change observed in Europe during the process of industrialization (Weeks, 2008; Kirk, 1996). However, it has been found that most countries have followed a similar trajectory to that of Europe. The demographic transition began as early as the 1700s in Western Europe, while in Eastern Europe it began later, but progressed more quickly (Chawla, Betcherman and Banerji, 2007). Worldwide, most countries have at least entered the first stages of the demographic transition and the global demographic transition is expected to be completed by 2100. In Europe, countries are currently in the final stage of transition, or have, in some cases, moved past it (Lee, 2003).

The demographic transition refers to the shift from high birth and death rates to low birth and death rates that countries undergo as they industrialize (Weeks, 2008; Kirk, 1996). During this transition, population growth rates first accelerate and then begin to slow once again (Lee, 2003). Changes in population size are accompanied by changes in life expectancy and age distribution driven by transitions in mortality, fertility, household structure and migration (Weeks, 2008; Lee, 2003).The transition is generally described in four stages: pre-industrial, early growth, late growth and stabilization, illustrated in Figure 2. During the first stage, birth rates and death rates are both at moderate or high levels, meaning that population growth is very low. During the second stage, mortality decreases while birth rates remain at or near pre-industrial levels, causing a dramatic increase in the population growth rate and steep population growth. Fertility levels then begin to decline, causing population growth to slow in the third stage. When fertility levels catch up to mortality levels population growth stops and the population stabilizes. This is the fourth stage of the demographic transition theory (Kirk, 1996).

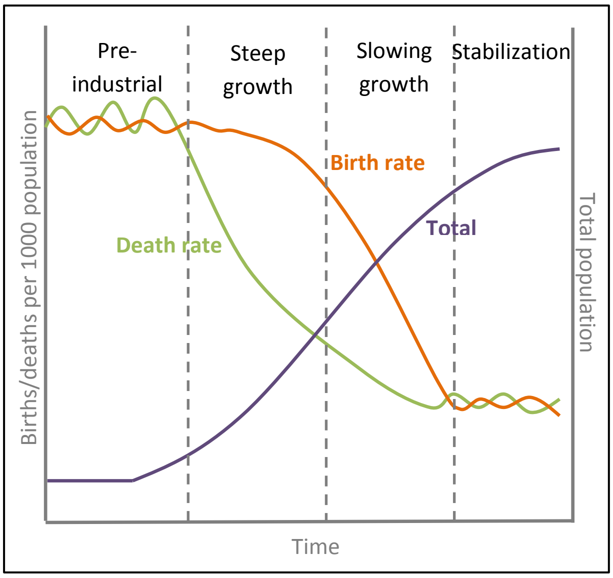


Figure 2. Demographic transition

However, the demographic transition in Europe has not culminated in stability with no population growth. While a balanced, stationary population with no population growth and little need for immigration was at first believed to be the final stage of the demographic transition, it has become clear that this is not the case (Lesthaeghe, 2010; van de Kaa, 2002). Fertility levels in Europe and other developed countries have continued to drop below replacement level (the number of children a woman must have in order to ensure replacement of her and her mate, approximately 2.1 children per woman in developed countries) which has led to negative rates of natural increase (Lesthaeghe, 2010; Kohler, Billari and Ortega, 2002). In Europe, only Iceland currently has an above replacement level fertility rate (Coleman and Rawthorn, 2011). For the time being, net migration has compensated for negative rates of natural increase and the population of Europe as a whole continues to grow, albeit at very slow rates. Net migration, however, has not in some countries and will not in the future of Europe as a whole, be able to compensate for the continued declines in fertility. For this reason, Europe has seen decline in population in certain countries and regions already and will, by approximately 2020, begin to experience decline as a whole continent (UN DESA, 2013a). Europe has moved towards ground not covered in the original demographic transition theory.

SDT is a term that is now used by some scholars to describe the persistent declines in fertility past replacement levels as well as other accompanying demographic changes (Lesthaeghe, 2010; van de Kaa, 2002). Section 2.2.3 will deal with it specifically; however, first a brief overview of the impact of the initial demographic transition in Europe on human settlement patterns will be given in order to set a base for later exploring the impact of the SDT and declining population on such development.

2.2.2 Changes in Human Settlement Patterns

Population is a key driver of land use and land cover change; however, its relative importance amongst other forces of change is difficult to quantify and is still unclear (Meyer and Turner II, 1992). Population growth in Europe has been accompanied by changes in technology, income, affluence and socio-cultural conditions which also contribute to land use and land cover change (Meyer and Turner II, 1992). Understandably, however, increasing populations must either be accommodated by a rise in population densities or by an increase in the extent of the built-up area, and it is clear that Europe experienced a rise in both as a result of the population growth during the demographic transition.

One important process which occurred was urbanization, the rise in the proportion of people who live in urban areas (Davis, 1965). With more people living and working in cities, a greater amount of supporting infrastructure as well as more commercial and industrial development is necessary and the size of the built-up area tends to grow. Meanwhile, population densities also increase as people are located closer together in non-rural communities. While urbanization is not generally linked directly with population growth, it is commonly linked with economic development.

Davis (1965) provided a powerful summary of the urbanization trend in Europe during the previous centuries. According to Davis (1965), urbanization was a finite process which took place during the transition of Europe from an agrarian society to an industrialized society and was typified as a cycle in the shape of an attenuated S, as seen in Figure 3. Before the industrial revolution, Europe's towns were small and growth was slow (Davis, 1965). As societies began to industrialize, they experienced a swift rise in urbanization. This portion of urban development is the first bend in the S-shaped curve of urbanization (Davis, 1965). Following this early rise, urban growth continued, but its pace gradually slowed. In the final phase, urban growth stagnated and, in some cases, even declined (Davis, 1965). While urban growth may have stagnated, Davis (1965) makes it clear that this does not mean that the number of urbanites decreased. On the contrary, he cautions that the slowing of urbanization is "more apparent than real: an increasing proportion of urbanites simply live in the country and are classified as rural" (Davis, 1965, p. 24).

Davis' (1965) S-shaped curve of urbanization clearly mimics the population change curve of the demographic transition theory, and it is clear that they are related. While it cannot be said that population change led to urbanization, it can be concluded that the same structural and cultural changes contributed to both urbanization and population change. However, while urbanization may have slowed in Europe, the size and extent of the built-up area has, for the most part, still increased. This is due to the increase in non-urban development, or suburban development, a second important land development process.

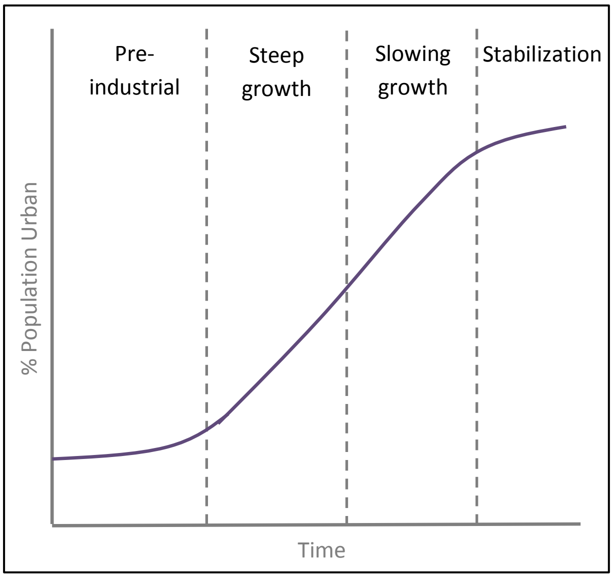


Figure 3. Urbanization model

Here, it is useful to examine van den Berg, et al.'s (1982) theory of cyclical urban growth and decline. They identified four stages of urban development: urbanization, suburbanization, desurbanization, and reurbanization. From the first stage, the extent of human settlement continuously increased. What changed was the distribution and composition of the population in what they term the core (urban area), ring and functional urban area (FUR) (van den Berg, et al., 1982). During the urbanization stage there was a swift growth in the size (both physical and population) of all areas. This is consistent with the initial phase of Davis' (1965) urbanization theory. Van den Berg, et al. (1982) identify that this took place in Western Europe during the industrial revolution and in Eastern Europe following WWII. During suburbanization, improvements in transportation and affluence allowed residential development to expand outside of the central city in the ring and FUR. Meanwhile, core employment continued to thrive and the suburbs and the central city were integrated functionally. This parallels the slowed urban growth in Davis' (1965) theory and illustrates why the built-up area continued to grow even if urbanization slowed. Increased congestion and dissatisfaction with urban life then began to build and led to the desurbanization stage when an increasing number of people moved to small and medium sized towns, leaving the core and even the suburbs of these cities, but still contributing to expanding land use. The fourth stage of van den Berg, et al.'s (1982) model is one of reurbanization or a return to the central cities. When their work was published in 1982, they were still unsure if this type of development would occur naturally in Europe and it is not the place of the current study to explore this. Instead, it is relevant that throughout the four stages of development, growth in built-up area was experienced, even if the distribution of population throughout the land changed.

Parallels can be seen between Davis' (1965) and van den Berg, et al.'s (1982) theories of urbanization in Europe and the demographic transition theory. Both population and urban development appear to have transitioned in similar manners from stability through rapid then slowing growth and back to stability as a result of the economic transformations of industrialization and modernization. And yet, the total amount of land dedicated to human settlement has grown over time. Due to suburbanization and desurbanization, it has indeed increased faster than the growth in the number of people living there (Meyer and Turner II, 1992). It is clear that population growth has been linked with increase in the amount of land devoted to human settlement (either urban, suburban or rural); however, as has been discussed, population in Europe is set in a declining trajectory and from here arises the main question of this research: will development continue to be coupled with population and therefore begin to decrease or will human settlement continue to grow?

2.2.3 The Second Demographic Transition (SDT)

Bongaarts (2001, p. 260 cited in van de Kaa, 2002) wrote:

> "If fertility in contemporary post-transitional societies had indeed leveled off at or near the replacement level, there would have been limited interest in the subject because this would have been expected. … However, fertility has dropped below the replacement level – sometimes by a substantial margin – in virtually every population that has moved through the demographic transition. If future fertility remains at these low levels, population will decline in size and age rapidly."

The SDT is a theory which provides a characterization and an explanation for what is seen as a new stage in countries' demographic development. It remains to be seen if the SDT will spread worldwide in the same manner as the initial demographic transition, or if it is a transition that is limited to developed or industrialized countries. However, for the time being, the characteristics of the SDT have at least been observed throughout Europe (Lesthaeghe, 2011, 2010; van de Kaa, 2002). This section will now examine the demographic characteristics of the SDT and its drivers.

The idea of a SDT was first put forward by van de Kaa and Lesthaeghe in 1996 and they remain the theory's main proponents (Lesthaeghe, 2011). They describe a new stage in the demographic development of industrialized countries that brings with it sustained, sub-replacement fertility levels, a diversification in living arrangements, a disconnection between marriage and procreation and no stationary population (Lesthaeghe, 2011). Specifically, the SDT is characterized by the following main features:

- a decrease in period total fertility rates (TFR),
- a decrease in the total first marriage rate coupled with an increase in the average age at first marriage,
- an increase in the divorce rate,
- an increase in the rate of cohabitation,
- an increase in the proportion of births out of wedlock, and
- a replacement of traditional means of contraception with modern means (van de Kaa, 2002).

Figure 4 shows a conceptualized depiction of the first and second demographic transitions, taken from van de Kaa (2002). While net migration was not included in the theory of the first transition, van de Kaa has added it to this figure because of its contribution to the SDT. Without positive net migration during the SDT, many countries which are currently growing in population would actually be experiencing declining populations (van de Kaa, 2002). Figure 5 shows the actual situation in Europe as a whole and in the four regions of Europe from 1950 to the current time and then projected to 2100 based on data from the UN World Population Prospects, 2012 Revision. It is clear from this figure that the demographic trajectory of Europe does indeed follow the path depicted in the SDT theory.

According to Lesthaeghe (2011), evidence of a SDT in Europe started in Scandinavia in the 1950s and spread to Northern and Western Europe followed by Southern Europe and finally Eastern Europe after the collapse of communism in 1989 (van de Kaa, 2002). By the second half of the 1960s, the TFR in these regions had dropped from its highs during the baby boom to below replacement (Lesthaeghe, 2011). Postponement of childbearing until later ages was and continues to be a contributing factor to declining fertility rates (van de Kaa, 2002).

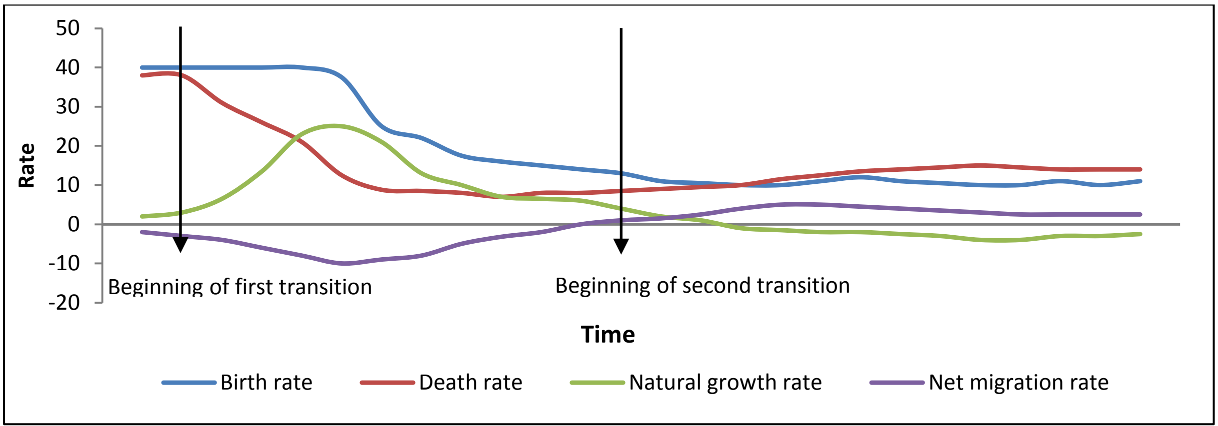


Figure 4. The Second Demographic Transition (SDT) model
Source: van de Kaa, 2002

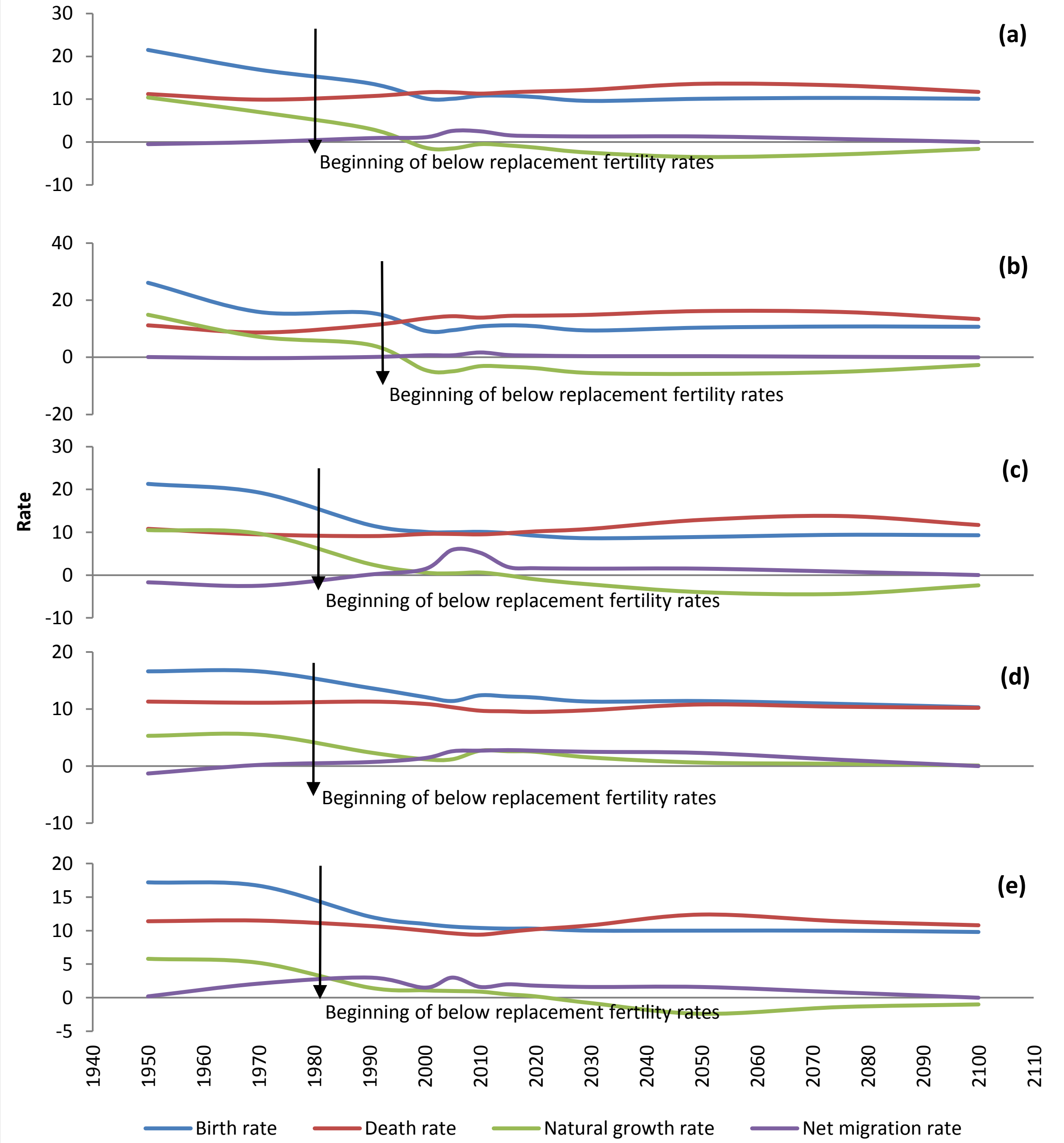


Figure 5. Demographic Change, 1950 to 2100

(a) Europe, (b) Eastern Europe, (c) Southern Europe, (d) Northern Europe, (e) Western Europe

Source: UN DESA, 2013b

Other characteristics of the SDT pertain to marriage. Since approximately 1965, marriage rates have declined and the mean age at first marriage has increased in Europe (Lesthaeghe, 2011; van de Kaa, 2002). Furthermore, divorce rates have increased and there has been a shift towards increased cohabitation, both before and after marriage (Lesthaeghe, 2011; van de Kaa, 2002). An increase in the percentage of extra-marital births has accompanied these trends (van de Kaa, 2002). The matrimonial transition, however, has not been as widespread as the fertility transition. In Southern Europe, specifically, cohabitation and extra-marital births are not yet the norm, although the latter has been increasing (Lesthaeghe, 2011). This could be, as Reher (1998) suggests, a function of differing family systems. While the Mediterranean region has a “strong family system”, where family ties are important throughout life and much financial and emotional support is derived from the family, Western and Northern Europe have a “weak family system”, where greater independence and gender equality decrease the importance of traditional family relations (Reher, 1998). Or, it could also merely be, as van de Kaa (2002) suggests, a reflection of lags and leads, where Southern Europe has, up until now, not caught up to the rest of Europe in terms of marriage characteristics.

A derivative of the marriage transition has been the diversification of household structures. Single person households are much more common throughout Europe today than they were in the 1960s. Additionally, people choose to live alone for longer periods before forming a union, whether this is marriage or cohabitation (Lesthaeghe, 2011). Likewise, the proportion of single parent households has also increased (Lesthaeghe, 2011).

Finally, the age structure of the population has continued to change. During the demographic transition, life expectancy continuously increased throughout much of Europe. Since the 1970s, its continued increase can be attributed to rising focus by individuals on preventing premature death by living in a healthy manner (van de Kaa, 2002). The exception is in Eastern Europe where life expectancies have either remained stagnant or declined, likely due to crisis conditions and lack of medical care and services (van de Kaa, 2002). With rising life expectancy and declining fertility rates, the population in general has aged (van de Kaa, 2002). There are fewer people being born, but greater numbers of people are surviving to ever higher ages. This may have implications for the housing diversity described above as well. A healthier, older population may serve to increase the number of one and two person households within a population. Crude mortality rates have, however, increased since the 1970s and this is a direct reflection of the aging population. As birth rates continue to fall, mortality rates overtake birth rates, which induces natural population decrease. This leads to overall population declines, unless net migration rates are sufficient to compensate for the population loss.

2.3 Conclusions

The aim of this section was to establish the theoretical framework for the analysis of European population change and its relationship with changes in nighttime lights. Since before the industrial revolution in Europe, population growth has been tied to growth in the amount of land dedicated to human settlement. However, it cannot be concluded that population growth has caused such development expansion. Rather, both processes have occurred simultaneously and in parallel, likely tied to industrialization and modernization, as explained by demographic transition theory and urbanization theory. Now, Europe has entered a period of population decline which leads to the question of whether human settlement patterns will be altered to reflect such decline. The three research questions identified in Section 1.3 were developed from within this framework and are aimed at narrowing the research gaps identified in the existing nighttime lights literature while incorporating relevant theories regarding demographic changes tied to population decline in Europe.

This thesis will evaluate the question of whether human settlement change and population change will continue to be coupled during periods of population decline, using the nighttime lights dataset over its full time series as a proxy for human settlement. It will first establish how both population and nighttime lights have changed between 1992 and 2012. It will then address the relationship between population change and change in nighttime lights and identify whether population decline is reflected in nighttime lights. Finally, it will draw from SDT theory in order to determine if other demographic changes that have been coupled with population decline in Europe can better explain the changes in nighttime lights.

Chapter 3: Methods and Data

This section is dedicated to a description of the study area, time frame, and data as well as the data collection methods that were used in this study. The methods of analysis will be covered later in Chapter 4, while the rationale for the selection of a quantitative method was covered in Section 1.4.

As has been detailed, nighttime lights data were the core dataset for this study and as such formed a large part of the methods and data preparation. Population data were used alongside this imagery to evaluate the connection between changes in population and human settlement patterns. Apart from nighttime lights imagery and population data, additional demographic data were also employed in order to understand the role of the SDT in relation to nighttime lights change.

3.1 Study Area

Europe was selected as the study area for this research for several reasons. First, Europe contains some of the only countries worldwide to be already experiencing population decline. Additionally, this decline is projected to continue in the countries where it has begun and to expand to additional countries in Europe. Just as Europe leads the world in the declining population trend, the continent was also one of the first to experience high population growth rates, starting in the 20th century. Today, we have seen that such a growth trajectory has spread worldwide. As such, it is relevant to study Europe as a possible example of what may occur worldwide with regards to declining populations. While it is still unclear if population decline will become a global phenomenon, it is nonetheless appropriate to examine Europe as a case study. Second, Europe is a data rich region, which is beneficial in time series analyses where multiple datasets are required. For the present research, accurate population data on a yearly basis was important and it was found that European countries provided free access to such data. Additionally, economic data was found to be available on a yearly basis throughout Europe. One limitation is that other demographic data, such as information on household size was only found for countries within the European Union, rather than for the entire continent. Finally, Europe presents a unified area within which to undertake analysis. Here there is the possibility of comparison between countries experiencing growth and countries experiencing decline as well as regional differences between Eastern, Western, Northern and Southern Europe; however, countries still share a somewhat common development trajectory, political climate and culture which would not be the case with a global study.

Figure 6 shows the countries which were selected to participate in the research, a total of thirty-five. Finland, Norway, Sweden, Iceland and Russia were excluded from the analysis because of decreased accuracy of the nighttime lights data. At the extreme north latitudes of these countries, fewer cloud-free observations are included into the data because observations that are not dark enough, such as those for the summer months when the sun sets late and for aurora activity, are filtered out (Henderson, Storeygard and Weil, 2012).

Figure 6. Study Area

Table 2. Temporal coverage of economic and demographic data

Country	Age structure	GDP	Single person households	Age leave home
Albania			n/a	n/a
Austria			1995-2001, 2003-2012 (17)	2004-2012 (9)
Belarus			n/a	n/a
Belgium			1996-2001, 2003-2012 (17)	2000-2012 (12)
Bosnia and Herzegovina			n/a	n/a
Bulgaria			2005-2012 (8)	2004-2012 (9)
Croatia		1995-2012 (18)	2003, 2010-2012 (4)	2002-2012 (11)
Czech Republic			2001, 2003, 2005-2012 (10)	2002-2012 (11)
Denmark			2003-2012 (10)	2010-2012 (3)
Estonia		1995-2012 (18)	2000-2012 (13)	2000-2012 (12)
France			1996-2002, 2004-2012 (17)	2003-2012 (10)
Germany			1995-2000, 2005-2012 (14)	2000-2012 (12)
Greece			1995-2001, 2003-2012 (17)	2000-2012 (12)
Hungary			2000-2002, 2005-2012 (11)	2000-2012 (12)
Ireland		2000-2012 (13)	1996-2001, 2003-2011 (16)	2006-2012 (7)
Italy			1996-2001, 2004-2012 (16)	2004-2012 (9)
Latvia			2000, 2002, 2005-2012 (10)	2002-2012 (11)
Liechtenstein	n/a	1992-2009 (18)	n/a	n/a
Lithuania			2000-2002, 2005-2012 (11)	2002-2012 (11)
Luxembourg			1995-2001, 2003-2012 (17)	2000-2012 (12)
Macedonia, FYR			n/a	2006-2012 (7)
Malta			2005-2012 (8)	2003-2012 (10)
Montenegro		1997-2012 (16)	n/a	n/a
Netherlands			1995-2002, 2005-2012 (16)	2000-2012 (12)
Poland			2000-2002, 2005-2012 (11)	2003-2012 (10)
Portugal			1995-2001, 2004-2012 (16)	2000-2012 (12)
Republic of Moldova			n/a	n/a
Romania			2000-2002, 2007-2012 (9)	2002-2012 (11)
Serbia			n/a	n/a
Slovakia			2003, 2005-2012 (9)	2003-2012 (10)
Slovenia			2000-2002, 2005-2012 (11)	2002-2012 (11)
Spain			1995-2012 (18)	2000-2012 (12)
Switzerland			2007-2012 (6)	n/a
Ukraine			n/a	n/a
United Kingdom			1995-2003, 2005-2012 (17)	2000-2012 (12)

* Numbers in brackets () denote the total coverage for the dataset in years

3.2 Temporal Scale

Twenty-one years of nighttime lights data, from 1992 to 2012, are available freely from the National Oceanic and Atmospheric Association's National Geophysical Data Center (NOAA-NGDC). As such, this was selected as the time span for this research. Population, economic and other demographic data were gathered for this time period, on a yearly basis. The economic and other demographic datasets were, for some countries, only available for more limited time periods. Table 2 shows the datasets where complete data was not available and identifies the time periods available for each country. Analyses involving these cases were done only for the period of time where data was available in each of the variables being considered.

3.3 Data Sources

3.3.1 DMSP-OLS Nighttime Lights

Nighttime lights data from the NOAA-NGDC was used. Since the mid-1970s, NOAA-NGDC has operated the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) and has digitally archived the imagery since 1992 (Baugh, et al., 2010). The sensors are flown on a sun-synchronous, low altitude, polar orbit and are designed to collect global cloud imagery (Baugh, et el., 2010; Elvidge, et al., 2009b; Elvidge, et al., 2004). The sensors have a resolution of 0.56 km; however, on-board averaging of this data into five by five blocks produces a "smoothed" dataset with a resolution of 2.7 km (Baught, et al. 2010; Elvidge, et al., 1999). Each sensor collects 14 orbits daily in 3000 km swaths which provide for complete global coverage four times during the day at dawn, daytime, dusk and nighttime (Elvidge, et al., 2009b; Elvidge, et al., 2004). At night, the visible band is intensified using a photomultiplier tube (PMT), which allows the sensors to detect clouds illuminated by moonlight (Baugh, et el., 2010; Elvidge, et al., 2009b; Elvidge, et al., 2004). The PMT boosts the detection of light and so allows the detection of lights such as human settlements, gas-flares, fires, fishing boats and the aurora (Baugh, et al., 2010; Elvidge, et al., 2009b; Elvidge, et al., 2004).

At a minimum, one satellite is operated each year. However, as the satellites and sensors age, the quality of data produced decreases and they must be replaced. In most years, there are therefore two satellites collecting data (Elvidge, et al., 2009b). The NOAA-NGDC produces three annual nighttime lights products from this data which are freely available to the public: cloud-free, average visible lights and stable lights composites. Additionally, a radiance calibrated and an average lights x pct dataset are produced from this data[7].

For this analysis, the annual stable lights composite (version 4) was used (NOAA-NGDC, 2014a). It provides data on the average visible band digital number (DN) values for all cloud-free observations. The DN values range from 0 to 63 and correspond with the brightness of the observed lighting (NOAA-NGDC, 2014b). It is filtered to remove ephemeral lights and background noise (such as auroras, forest fires, lights from fishing vessels and reflections of moon or starlight) so that only persistent surface lights remain (Elvidge, et al., 2013). A series of algorithms are used to select the best data to include within the composite image and the data is reprojected into 30 arc-second grids, between the latitudes of 65° S and 75° N (Baugh, et al., 2010). Baugh, et al. (2010) provides an in depth explanation of the processing required to generate the stable lights composite.

The stable lights dataset was selected because it provides a worldwide view of human development from space. It is versatile in that the sensors are able to detect faint light sources from rural areas as

[7] See NOAA-NGDC, 2014b for a description of each of these datasets

well as bright lights from urban areas and, since it contains DN numbers, differentiation between different types of light sources can be made (Elvidge, et al., 2013). Furthermore, it is consistently available on a yearly basis, which is not the case with many of the other nighttime lights products.

Known Issues with DMSP-OLS Data

Due to the coarse spatial resolution, high sensitivity and limited dynamic range of the sensors, the DN values saturate over urban areas, meaning that analysis in city centres becomes limited (Baugh, et al., 2010; Doll, 2010b; Elvidge, et al., 2009b). Furthermore, the datasets overestimate the actual size of lighting on the ground, a phenomenon referred to as blooming. Elvidge, et al. (2009b), found that this is due to the large OLS pixel size combined with its ability to detect sub-pixel light sources and to geolocation errors. They also indicated that scattering of light in the atmosphere, reflectance of light on adjacent water bodies and detection of terrain illuminated by scattered light from very bright urban areas could also generate overestimated areas, although they did not test these factors (Elvidge, et al., 2009b). Finally, the OLS has no on-board calibration for the visible band. Each sensor has different detection limits and saturation radiances and degrades at a different rate through time. Furthermore, gain adjustments on individual sensors are not recorded and can therefore not be used for calibration. Thus, DN values have different meanings in each composite and cross-year analysis is not assured (Elvidge, et al. 2013; Elvidge, et al. 2009b). Elvidge, et al. (2013; 2009b) developed a regression based intercalibration technique to calibrate composites against a base composite and allow for cross-year analysis. This technique was used in this study and will be subsequently explained.

3.3.2 Population

Population data was downloaded from the World Bank World Development Indicators open data database (The World Bank Group, 2014). This data is gathered by the World Bank from various regional and country-specific sources for all countries worldwide and is available yearly from 1960 to the present. Total population counts were downloaded for the thirty-five countries in the study area on a yearly basis from 1992 to 2012. Total population counts for each country come from one or a combination of the following sources:

- United Nations Population Division. World Population Prospects,
- United Nations Statistical Division. Population and Vital Statistics Report (various years),
- Census reports and other statistical publications from national statistical offices, and
- Eurostat: Demographic Statistics (The World Bank Group, 2014).

Additionally, data regarding the percentage of the population between 0 and 14 and over 65 was downloaded for each country on a yearly basis from 1992 to 2012. This data is gathered by the World Bank from The United Nations Population Division's World Population Prospects (The World Bank Group, 2014). Age-specific population data was not available for Liechtenstein (see Table 2).

3.3.3 Gross Domestic Product (GDP)

Official GDP data were also obtained from the World Bank World Development Indicators open data database (The World Bank Group, 2014). Data were downloaded for each study country on a yearly basis from 1992 to 2012. For five countries data was not available for the entire twenty-one year period (see Table 2). The official GDP data represents the value of the gross output produced in a country minus the value of intermediate goods and services consumed in production. All GDP data are expressed in constant 2005 US dollars (USD). Since the purchasing power of currency changes over time due to inflation, the use of the constant value allowed for time series comparison of the data. In order to allow comparison across Europe, a standard currency was necessary. The standardized currency available from the World Bank was USD and this was deemed appropriate for use. The figures are converted from local currencies using 2000 official exchange rates.

3.3.4 Other Demographic data

Two additional demographic datasets were also used. These included the proportion of the population living in single person households and the average age of young people leaving the parental household. Both were accessed from the Eurostat Statistical Database (Eurostat, 2014). Data on the proportion of the population living in single person households is available from 1995 to 2012 for the European Union countries and Switzerland; however, the time series was not continuously available in all countries (see Table 2). Data for this dataset is compiled from at least three different sources. For the period up until 2001, the primary source was the European Community Household Panel (ECHP) for countries that were then members of the European Union and national statistics for the other countries. Since 2001, the primary source has been European Statistics on Income and Living Conditions (EU-SILC). However, EU-SILC was not launched simultaneously across the European Union. As such, in the interim, where available, national statistics supplemented the data (Eurostat, 2014). Data on the average age of young people leaving the parental household was available for a more limited time period, from 2000 to 2012, for European Union member states and some candidate countries (see Table 2). This data is based on the EU Labour Force Survey which is compiled on a quarterly basis and provided by Eurostat as a yearly aggregation (Eurostat, 2014).

3.4 Data Preparation

Having downloaded the average stable lights dataset from the NOAA-NGDC, pre-processing of the dataset was required in order to proceed with the analysis. As mentioned previously, the OLS has no on-board calibration for the visible band and in-flight gain changes are not reported. Therefore, comparison across composites is not possible since the DN values from each composite have a different base point. The downloaded composites were therefore intercalibrated for cross-year analysis and then further prepared for this study.

Each composite was cut over the landmass of Europe to produce a total of 33, 4800 by 3950 pixel composites, covering 30.2°N to 63°N and 10.1°W to 39.9°E. These represent 21 years of data with some years having multiple composites as a result of multiple satellites being in orbit.

The first step was to remove gas-flares. Gas flaring is used to dispose of dissolved natural gas from petroleum in production and processing facilities (Elvidge, et al., 2009b). Gas-flares are thus not representative of human settlement and it was deemed appropriate to exclude them from the analysis. While all gas-flares from European countries are located offshore and would therefore not impact the planned analysis directly, they were nonetheless removed so that they would not be present during the intercalibration procedure. The removal of gas-flares was done using a set of ESRI shapefiles available from NOAA-NGDC which contain polygons outlining the location of gas flares for each country (NOAA-NGDC, 2014c). These locations were identified through analysis of DMSP-OLS nighttime lights imagery, details of which can be found in Elvidge, et al. (2009b).

The second step in the preparation of the nighttime lights dataset was intercalibration, that is, standardizing DN values across composites. The intercalibration procedure developed by Elvidge, et al. (2009b) and used again in a forthcoming book chapter (2013) is aimed at overcoming the limited comparability of the DMSP-OLS data by calibrating each composite against one base composite. It is a regression based technique that works under the assumption that the lighting levels in a reference area have remained relatively constant over time and can therefore be used as the dependent variable.

First, F182010 was chosen as the base composite because it contained the highest DN values overall, as seen in Table 3. In their study, Elvidge, et al. (2013; 2009b) selected F121999 as the base composite. The difference in the selection is attributed to the fact that Elvidge, et al. (2013; 2009b) were intercalibrating a world-wide dataset while the present study examines only the European case. Next, a reference area was selected. NUTS 2 regions with large urban areas were examined to find settlements which had very little change in lighting over time. Following Elvidge, et al. (2013; 2009b), the DN values for each region were plotted in a scattergram against the base composite of F182010. Consistency over time is represented by scattergrams with a clearly defined diagonal axis, minimal width along the primary axis and few outliers. Of the candidate regions tested, it was determined that Sicily provided the best fit to these criteria, consistent with the findings of Elvidge, et al. (2013; 2009b).

Next, a second order regression model was developed for each composite. The calculation is of the following form:

$$y = C_0 + C_1 x + C_2 x^2$$

Table 3. Digital number (DN) value summary statistics by composite

Satellite	Year	Min	Max	Average	Standard Deviation
F10	1992	0	63	2.919	8.030
	1993	0	63	2.875	7.732
	1994	0	63	2.957	7.956
F12	1994	0	63	3.182	8.579
	1995	0	63	3.636	9.032
	1996	0	63	3.442	8.591
	1997	0	63	3.700	9.075
	1998	0	63	4.111	9.682
	1999	0	63	3.922	9.776
F14	1997	0	63	2.851	7.798
	1998	0	63	3.195	8.317
	1999	0	63	3.197	8.207
	2000	0	63	3.320	8.341
	2001	0	63	3.428	8.700
	2002	0	63	3.171	8.444
	2003	0	63	3.403	8.794
F15	2000	0	63	3.958	9.109
	2001	0	63	4.027	9.241
	2002	0	63	4.050	9.283
	2003	0	63	3.002	7.713
	2004	0	63	3.047	7.820
	2005	0	63	3.345	8.238
	2006	0	63	3.260	8.221
	2007	0	63	3.139	8.066
F16	2004	0	63	3.351	8.292
	2005	0	63	3.220	8.009
	2006	0	63	3.410	8.586
	2007	0	63	3.823	9.140
	2008	0	63	3.795	9.145
	2009	0	63	3.676	9.016
F18	2010	0	63	6.066	12.025
	2011	0	63	4.514	10.011
	2012	0	63	5.029	10.913

Table 4 shows the resulting calibration coefficients. These coefficients were applied to each composite so that a new value (*y*) was calculated based on the original value (*x*). Any values over 63 were truncated so that the range of the values remained between 0 and 63.

Two methods were used to evaluate the results of the intercalibration procedure. First, a second summary of the DN values for each composite was created, as seen in Table 5. As can be seen, the intercalibration procedure served to raise the average DN values closer to that of F182010. Second, the sum of lights (SOL), the sum of all of the DN values for a specific region, was calculated for each country before and after calibration. The results of this comparison are shown in Figure 7. As can be seen, the different satellite years show better convergence in some countries than in others. The lack of convergence in some cases is attributed to changes in overpass times of satellites, which can differ by as much as two hours and lead to differences in the amount of lighting activity (Elvidge, et al., 2013).

Table 4. Intercalibration coefficients

Satellite	Year	C_0	C_1	C_2
F10	1992	0.0577	1.8322	-0.0140
	1993	-0.1031	1.9334	-0.0156
	1994	0.0711	1.9056	-0.0155
F12	1994	0.0996	1.5284	-0.0086
	1995	-0.0196	1.6398	-0.0108
	1996	0.0850	1.7066	-0.0119
	1997	-0.0270	1.5579	-0.0092
	1998	-0.0345	1.4509	-0.0078
	1999	0.0394	1.3969	-0.0070
F14	1997	-0.0204	2.1047	-0.0186
	1998	0.1002	2.0889	-0.0188
	1999	-0.0281	1.9474	-0.0161
	2000	0.0920	1.8814	-0.0153
	2001	-0.0131	1.7926	-0.0135
	2002	0.0784	1.7011	-0.0122
	2003	-0.0185	1.7744	-0.0133
F15	2000	-0.1015	1.4326	-0.0073
	2001	-0.0916	1.4454	-0.0071
	2002	-0.0326	1.3646	-0.0060
	2003	-0.0387	2.0021	-0.0168
	2004	0.0820	1.8514	-0.0144
	2005	-0.0311	1.7861	-0.0130
	2006	-0.0035	1.8146	-0.0135
	2007	0.1053	1.8927	-0.0151
F16	2004	0.0017	1.6334	-0.0107
	2005	-0.0734	1.8601	-0.0143
	2006	-0.0087	1.5660	-0.0091
	2007	-0.0205	1.3583	-0.0060
	2008	-0.0179	1.4378	-0.0073
	2009	0.1349	1.5622	-0.0095
F18	2010	0.0000	1.0000	0.0000
	2011	0.0938	1.2698	-0.0055
	2012	0.0122	1.1210	-0.0024

Table 5. DN value summary statistics by composite after intercalibration

Satellite	Year	Min	Max	Average	Standard Deviation
F10	1992	0	60	4.330	10.390
	1993	0	60	4.440	10.230
	1994	0	59	4.505	10.309
F12	1994	0	62	4.156	10.189
	1995	0	60	4.880	10.736
	1996	0	60	4.839	10.595
	1997	0	62	4.853	10.664
	1998	0	60	5.063	10.813
	1999	0	60	4.691	10.754
F14	1997	0	60	4.696	10.648
	1998	0	58	5.194	11.191
	1999	0	59	4.986	10.697
	2000	0	58	5.021	10.605
	2001	0	59	4.956	10.750
	2002	0	59	4.411	10.209
	2003	0	59	4.855	10.675
F15	2000	0	61	4.914	10.264
	2001	0	63	5.058	10.607
	2002	0	62	4.903	10.330
	2003	0	60	4.882	10.457
	2004	0	60	4.658	10.040
	2005	0	61	4.925	10.465
	2006	0	61	4.825	10.475
	2007	0	59	4.822	10.455
F16	2004	0	60	4.568	9.916
	2005	0	60	4.878	10.317
	2006	0	63	4.573	10.275
	2007	0	62	4.590	10.660
	2008	0	62	4.736	10.329
	2009	0	61	4.876	10.625
F18	2010	0	63	6.066	12.025
	2011	0	58	5.097	10.369
	2012	0	61	5.313	11.065

Once the composites were intercalibrated, the third step was to average the composites from the same year that were generated by different satellites. The composite for F142002 was removed from the average because much of the Northern Hemisphere was found to be blacked out in this composite. The result of the averaging was 21 composites each representing one year of nighttime lights between 1992 and 2012.

The final step was to reproject the dataset into an equal area projection. Because the aim of the present study includes an examination of the size and extent of lit areas, an equal area projection was deemed necessary. Equal area projections preserve area while sacrificing other properties, most notably shape. As recommended by the European Environment Agency (2012), the Lambert Azimuthal Equal Area projection was selected and each yearly composite was reprojected using a nearest neighbour resampling technique and a cell size of 1 km^2.

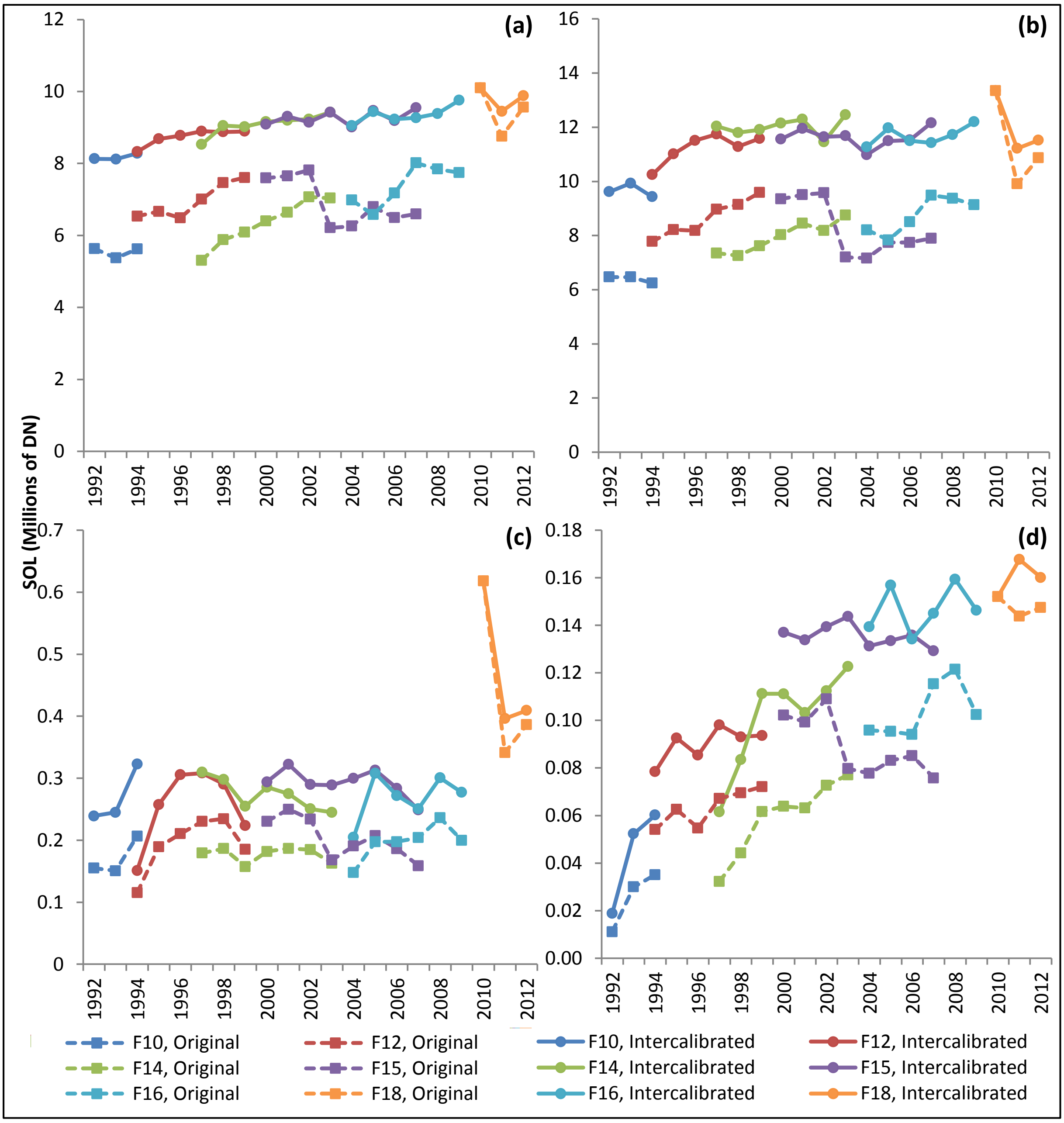


Figure 7. Intercalibration validation, SOL, selected countries, 1992 to 2012

(a) Italy. The best case of convergence. During years when two satellites collected data, intercalibration has led to very similar SOL values between different satellites, (b) France. Similarly effective intercalibration, (c) Latvia. Reduced level of convergence. Some years still exhibit large differences in SOL between different satellites, (d) Albania. Lack of convergence. In the most extreme case, Albania shows little improvement between the original and intercalibrated datasets

The final dataset is a set of 21 yearly composites in an equal area projection that have been intercalibrated and which contain only evidence of human settlement through nighttime lights (gas-flares have been removed).

In order to be comparable with the country level population, GDP and other demographic data, the nighttime lights data needed to be aggregated to the country level. It was decided to do this in two ways: as a sum of the DN values of all pixels within a country and as the total number of lighted pixels. The first measure, the SOL, is a measure of the total intensity of lighting, while the second measure, referred to as lighted area, is a measure of the total expanse of the lighted region.

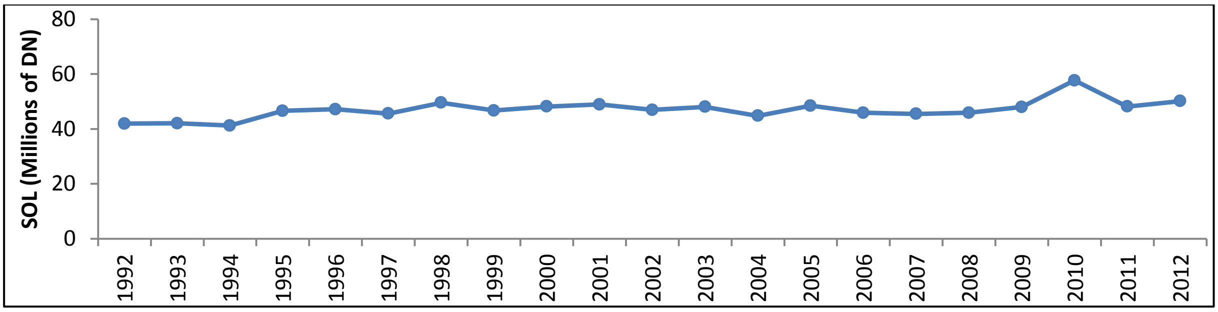


Figure 8. SOL, Europe, 1992 to 2012

The population, GDP and other demographic data required little pre-processing. The country names used by the World Bank and Eurostat differed, so these were standardized in order to allow comparison and linking of the various tables.

Finally, each of the datasets was examined for extreme outliers within the time series. It was found that during the year 2010 there was an uncharacteristic spike in the level of lighting detected in the DMSP-OLS dataset, even after calibration. Figure 8 illustrates this for Europe as a whole. It was deemed that this outlier was likely caused by a change in satellite, which came into effect in 2010. While intercalibration with 2010 as the base year removed some of the discrepancy, it was not able to do so completely and therefore 2010 was removed from the analysis on a country by country basis when its lighting levels were deemed to be uncharacteristically high. Apart from this, 2009 was a slight outlier in overall GDP for Europe, which may be attributed to the financial crisis of 2008. Additionally, in 2001, the average proportion of people living in single person households throughout Europe dipped slightly from its generally increasing trend. However, in contrast to the spike in lighting levels, these outliers were deemed to reflect structural or demographic phenomena and not weaknesses in data.

3.5 Conclusions

Based on the accuracy and availability of socio-economic indicators as well as the fact that Europe is the only region worldwide to have begun experiencing consistent population declines, Europe was selected as the study area for this analysis. Seven datasets were collected in order to answer the research questions set out in Section 1.3. The two core datasets were the DMSP-OLS nighttime lights dataset and World Bank World Development Indicators population counts. Additionally, the percentage of the population younger than 15 and older than 65, the GDP in 2005 USD, the proportion of the population living in single person households and the average age of young people leaving the parental household were also collected. The time frame for the analysis was dictated by the availability of the nighttime lights dataset, which ranges from 1992 to 2012, since all other data could, for the most part, be gathered for this time span.

The result of the data collection and data preparation stages of the study as described in this section were country-level totals of each of the datasets, with the nighttime lights dataset being summarized in two separate totals: SOL and lighted area. These summary statistics were then employed in the analysis in order to answer each of the research questions. The following section sets out the results of this analysis.

Chapter 4: Results

The results section of this thesis is divided into three sections aimed at answering each of the three research questions. The first one presents a preliminary exploration of the data and its patterns. The second examines the relationship between population and lighting and its trends and the third looks further at other explanatory variables for these relationships. The sections are presented as follows. First, a brief explanation of the analysis methods is provided and second, the results of the analysis are presented. A discussion regarding the results follows in Section 5.1.

4.1 Patterns and Change in Population and Nighttime Lights

The first part of the present study deals with understanding the changes over time within the two main datasets and with identifying patterns within each. This section therefore turns first to an analysis of the population dataset and second to that of the nighttime lights dataset.

4.1.1 Methods: Population Change

The overall change in population between 1992 and 2012 was first calculated. However, measuring population change from 1992 to 2012 can hide population fluctuations within the 21 year period, most relevantly in countries where population decline began sometime during this period but in which it did not drop to levels lower than those at the beginning of the period. Therefore a more specific examination of population trends was undertaken.

The population growth for each country was examined to determine if there was a shift from positive to negative (or negative to positive) growth during any point within the study period. If a reversal that persisted for at least three years was identified, this was noted as a shift in the population trend for that country. In this way, each country was divided into periods of growth, decline or stability. The population for each year relative to the population in the starting year (1992) was then plotted on a scatterplot and a line of best fit drawn for each period of population change. The slope of such a line therefore reflected the average percent population growth over each period. Positive slopes were assigned as growing populations and negative slopes as declining populations. Stable populations were those with a slope between -0.001 and 0.001 (or +/- 0.1 percent growth). The result of this exercise was a division of European countries into a population change typology composed of six groups: steadily growing, steadily declining, u-shaped, growing then declining, erratic and stable.

4.1.2 Results: Population Change

Despite the fact that the European population as a whole is still increasing in 2014, several European countries have already begun to experience population decline. Figure 9 maps the change in population from 1992 to 2012 for the study region. It is clear from this figure that while Western Europe generally experienced growing populations during the study period, the East experienced consistent decline.

Table 6 is a more specific examination of the population trajectory of each country. The typology divides Europe into six groups based on the type of population change experienced by each country over the 21 year study period. Each group is explained below and an example of the population change from each is show in Figure 10.

Figure 9. Population change, Europe, 1992 to 2012

Table 6. Population typology

Steadily growing	Steadily declining	U-shaped	Growing then declining	Erratic	Stable
Austria	Albania	Italy	Germany	Bosnia and Herzegovina	Slovakia
Belgium	Belarus	Czech Republic	Greece	Croatia	
Denmark	Bulgaria	Macedonia, FYR	Portugal	Poland	
France	Estonia	Montenegro	Serbia		
Ireland	Hungary	Slovenia			
Liechtenstein	Latvia				
Luxembourg	Lithuania				
Malta	Republic of Moldova				
Netherlands	Romania				
Spain	Ukraine				
Switzerland					
United Kingdom					

Steadily Growing

These are countries where population growth occurred consistently over the entire study period. The countries which experienced steady growth are located exclusively in Western Europe.

Steadily Declining

These are countries that experienced continuously declining population over the entire study period and are located exclusively in Eastern Europe.

U-shaped

These are countries that experienced declining populations for some period of time but then began to experience population growth. For the three countries in this category, the shift from declining population to growing population came between 1998 and 2002. The countries which experienced u-shaped population change are located in Eastern Europe. Italy was placed in this group as well; however, rather than decreasing then increasing in population, it had a stable population until 2001 and then experienced an increase.

Growing then Declining

In contrast to countries that experienced u-shaped population change, these countries started out with growing populations then hit a peak after which populations began to decline. Three are located in Western Europe, while one is in Eastern Europe. For the three in Western Europe, decline began between 2003 and 2010, while for the one in Eastern Europe, decline began in 1995.

Erratic

The population in these countries was not consistently growing or declining, nor did it fit within the u-shaped or growth followed by decline patterns. Instead, it fluctuated between growth and decline throughout the period. The countries experiencing erratic population change are located in Eastern Europe.

Stable

Only Slovakia experienced stable population change during the study period. This was identified as an overall trend of less than 0.1 percent growth or decline.

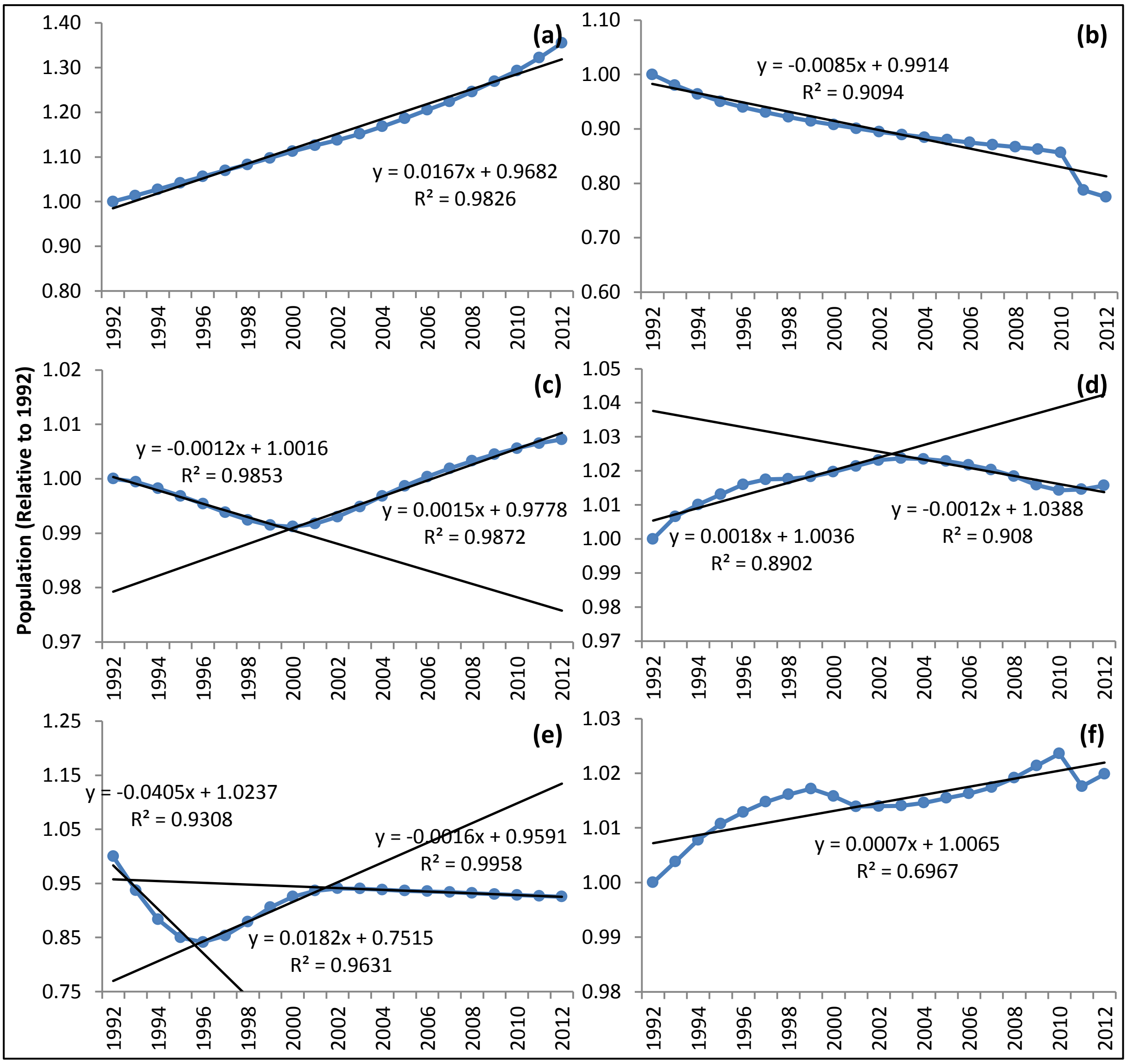


Figure 10. Population change, selected countries, 1992 to 2012
(a) Luxembourg – steadily growing, (b) Latvia – steadily declining, (c) Montenegro – u-shaped, (d) Germany –growing then declining, (e) Bosnia and Herzegovina –erratic, (f) Slovakia – stable

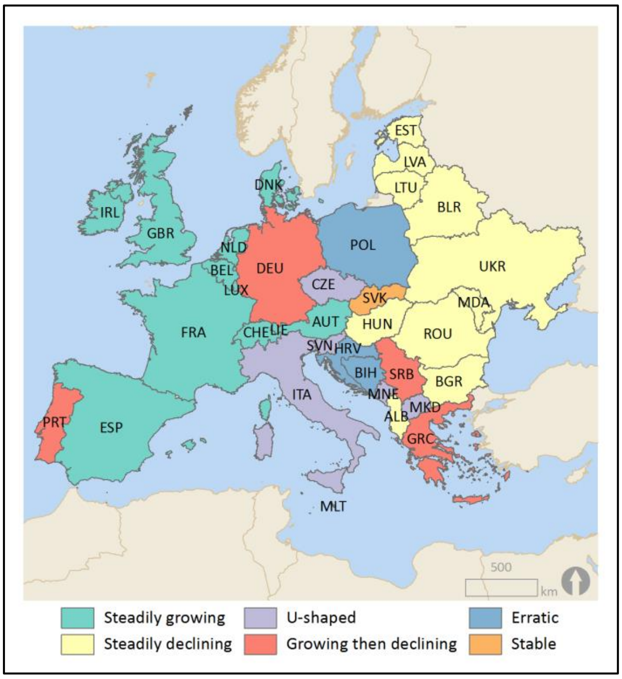


Figure 11. Population typology

Figure 11 maps the typology. In this case, the East-West division that was seen earlier in positive and negative population growth can still be seen. Western European countries tend to have experienced more steady increasing populations, while Eastern European countries have experienced more fluctuation within their population trajectory.

4.1.3 Methods: Nighttime Lights Change

Just as with population, the total change in lighted area and SOL from 1992 to 2012 were first calculated. Then, a typology similar to that of population was also created following the same method. Countries were grouped into the following six categories: steadily growing, slowed increase, steadily declining, u-shaped, growing then declining and stable. The groupings were done for SOL and lighted area separately.

In order to continue to explore the links or differences between lighted area and SOL change over time, a regression between the lighted area and the SOL was calculated for each country. The strength of this relationship indicates how closely lighted area and SOL are related within each country, while its direction indicates whether change in lighted area and SOL are coupled or whether they are opposed.

To further illustrate the changes in lighting, and specifically in lighted area, an RGB composite map of three time periods (1992, 2002, and 2012) was developed. This map visually illustrates the change in lighted area at the pixel level by combining a binary version of each composite assigned to the red, green and blue bands respectively. The combination of the three bands results in eight colour combinations, which each represent a different type of change, as summarized in Table 7.

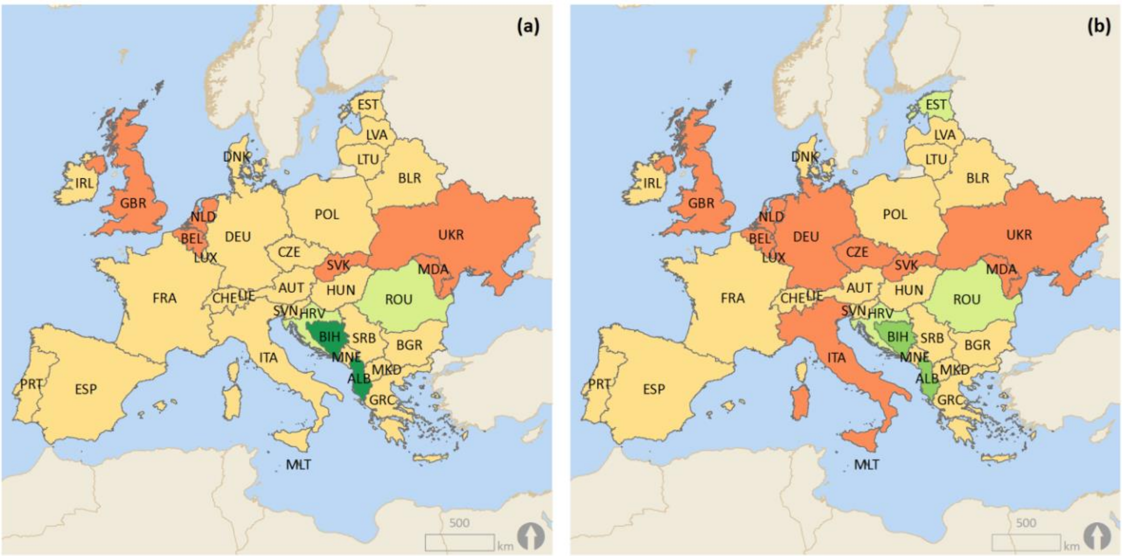
Table 7. RGB composite colour interpretation

Pattern	Interpretation	Colour
Decline	Decline: Lighting discontinued after 1992	Red
	Late decline: Lighting discontinued after 2002	Yellow
Growth	Growth: Lighting appears after 1992	Light blue
	Late growth: Lighting appears after 2002	Blue
Unstable	Growth then decline: Lighting appears after 1992 then is discontinued after 2002	Green
	Decline then growth: Lighting discontinued before 2002 then reappears after 2002	Purple
No change	Lighted: Always lighted	White
	Not lighted: Never lighted	Black

4.1.4 Results: Nighttime Lights Change

Both the SOL and total lighted area increased between 1992 and 2012 in Europe as a whole. The SOL increased by approximately 20 percent while the lighted area increased by approximately 42 percent. This large difference in their growth could be for two reasons. First, because it is known that the light intensity measure saturates at a value of 63, increasing light intensity in areas that have already reached this level is not captured by the satellites and therefore not incorporated into the SOL. Second, it could reflect that the newly lighted pixels are lit at low intensity levels, likely in rural or suburban areas.

Figure 12 maps the changes in lighting for each country. Lighted area grew in 32 countries and SOL in 28. Four countries (Belgium, Malta, Netherlands and the United Kingdom) experienced growth in lighted area while experiencing decline in SOL. The reasons for this will be explored later in this section. However, first, just as with population, it was of interest to understand the internal dynamics of change within the 21 year period. Table 8 presents the results of the typology analysis, which are summarized below.



Standard deviations	SOL (a)	Lighted area (b)
	% growth 1992 to 2012	
< -1,5		
-1,5 to -0,50	-54.3% to -2.6%	-17.0% to 23.8%
-0,50 to 0,50	-2.6% to 203.6%	23.9% to 212.1%
0,50 to 1,5	203.7% to 409.9%	212.2% to 400.4%
1,5 to 2,5	410.0% to 616.1%	400.4% to 820.0%
> 2,5	616.2% to 1011.7%	

Figure 12. Nighttime lights change, 1992 to 2012
(a) SOL change, (b) Lighted area change

Table 8. Nighttime lights typology

Steadily growing	Slowed increase	Steadily declining	U-shaped	Growing then declining	Stable
SOL change					
Albania Austria Estonia Ireland Latvia Liechtenstein Lithuania Montenegro Poland Portugal Romania Serbia Spain Switzerland	Bosnia and Herzegovina Croatia Greece Slovenia	Belarus Slovakia Ukraine	Republic of Moldova	Macedonia, FYR	Belgium Bulgaria Czech Republic Denmark France Germany Hungary Italy Luxembourg Malta Netherlands United Kingdom
Lighted area change					
Austria Belarus Bulgaria Denmark Estonia Latvia Lithuania	Liechtenstein Switzerland	Republic of Moldova Ukraine		Albania Bosnia and Herzegovina Croatia France Greece Hungary Ireland Italy Macedonia, FYR Montenegro Poland Portugal Romania Serbia Slovakia Slovenia Spain United Kingdom	Belgium Czech Republic Germany Luxembourg Malta Netherlands

Steadily Growing

These are countries where SOL or lighted area was steadily growing over the entire study period. For both SOL and lighted area there are more located in Eastern than Western Europe, but the split is almost even. Only four countries had steady growth both in SOL and lighted area; however, of those only Austria had growth at similar rates. In the others, all in Eastern Europe, lighted area grew faster than SOL. This is illustrated in Estonia, the most extreme example of disparate growth, in Figure 13a.

Slowed Increase

Several countries experienced growth in SOL or lighted area that slowed or even stabilized at some point. For SOL there are four countries in this group, three in Eastern and one in Western Europe, while for lighted area there are two, both in Western Europe. No country experienced a slowed increase in both SOL and lighted area. The slowing of lighting growth occurred for all countries sometime between 1998 and 2000. Figure 13b shows Croatia, a typical example of slowed increase.

Steadily Declining

These are countries that experienced continuously declining SOL or lighted area and are all located in Eastern Europe. Ukraine is the only country where both SOL and lighted area declined steadily.

U-shaped

The only u-shaped lighting change was in Moldova with respect to SOL, where the SOL decreased at a moderate rate until 2007 when it began to increase at a moderate rate, as shown in Figure 13c.

Growing then Declining

These countries started out with growing SOL or lighted area then hit a peak after which they began to decline. Only one country, Macedonia, fits this pattern with respect to SOL; however, a large majority of the countries are found within this group in terms of their lighted area change. The peak in lighted area was experienced by the countries in this group between 2000 and 2012.

Stable

Twelve countries experienced stable SOL change during the study period, ten in Western and two in Eastern Europe. Of these, five of the Western European countries also experienced stable lighted area change during the period, while one from Eastern Europe did. Stable change was identified as an overall trend of less than 0.9 percent growth or decline.

The results of the regression between SOL and lighted area are reported in Table 9. In most countries SOL and lighted area have a significant and positive relationship. The relationship is weak in Ukraine and Bulgaria, while in Lithuania, Greece, Albania, Bosnia and Herzegovina and Ireland it is very strong. There appears to be little regional influence on the strength of the correlation between SOL and lighted area.

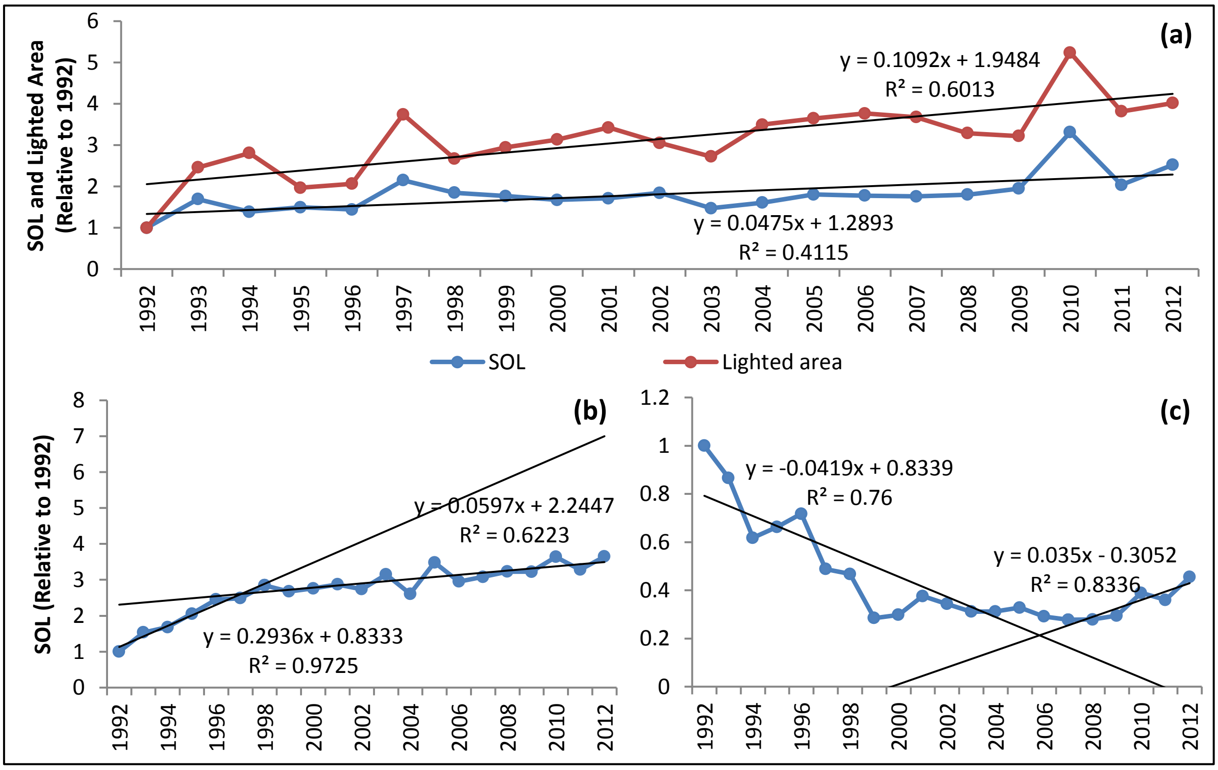


Figure 13. Nighttime lights change, selected countries, 1992 to 2012
(a) SOL and lighted area change in Estonia – an example of steadily growing nighttime lights in both SOL and lighted area, (b) SOL change in Croatia – an example of slowed increase change, (c) SOL change in Moldova – an example of u-shaped change

Table 9. Correlation SOL v. lighted area

Country	Pearson's R	R^2	Outliers
Albania	0.92 ***	0.85	
Austria	0.78 ***	0.61	
Belarus	0.85 ***	0.73	
Belgium	-0.29	0.09	1992, 1993, 1994
Bosnia and Herzegovina	0.93 ***	0.87	
Bulgaria	0.44 *	0.20	1992
Croatia	0.88 ***	0.77	
Czech Republic	0.29	0.09	Not a linear relationship
Denmark	0.32	0.10	
Estonia	0.80 ***	0.63	2010
France	0.73 ***	0.53	
Germany	0.21	0.04	2010
Greece	0.90 ***	0.80	1992
Hungary	0.81 ***	0.65	
Ireland	0.94 ***	0.88	
Italy	0.75 ***	0.56	
Latvia	0.72 ***	0.51	2010
Liechtenstein	0.74 ***	0.55	
Lithuania	0.90 ***	0.80	2010
Luxembourg	0.24	0.06	Not a linear relationship
Macedonia, FYR	0.89 ***	0.78	1992
Malta	--	--	No change in lighted area
Montenegro	0.87 ***	0.76	
Netherlands	-0.26	0.07	1992, 1993, 2009
Poland	0.84 ***	0.70	
Portugal	0.89 ***	0.79	
Republic of Moldova	0.79 ***	0.62	
Romania	0.87 ***	0.76	
Serbia	0.72 ***	0.52	
Slovakia	0.60 ***	0.36	
Slovenia	0.65 ***	0.43	1992
Spain	0.83 ***	0.68	
Switzerland	0.71 ***	0.51	
Ukraine	0.43 **	0.19	
United Kingdom	-0.19	0.04	

* Significant at 0.1 level, ** 0.05 level, *** 0.01 level

In Belgium, Netherlands, the United Kingdom, Malta, Germany, Luxembourg, Czech Republic and Denmark there is no significant relationship between the SOL and lighted area. Throughout the study period, less than 1 percent of the area of Belgium, Netherlands, Luxembourg and Malta was not lighted. In fact, Malta was completely lighted during the entire period. This is likely an important reason for the lack of a significant correlation between lighted area and SOL since even a slight change in SOL has a large influence on the linearity of the relationship between the two variables. The fact that there is no relationship between the two also motivates why there would be overall growth in lighted area but decline in SOL within these countries, as noted earlier. Another factor which could contribute to the lack of a statistically significant relationship is that of these countries Belgium, Luxembourg, Czech Republic, Malta, Germany and Netherlands experienced stable lighted area and SOL change over time. This means that minor variations in either variable were likely contributed to in large part by fluctuations in the sensor calibration. These variations are therefore not likely to correlate strongly over time. The outlier here is the United Kingdom. It has neither a low percentage of unlit area, nor did it experience both stable SOL and lighted area change. Instead, it experienced stable SOL change accompanied by u-shaped change in lighted area. Therefore, its lighted area was much more variable than its SOL and as such there is not a strong enough linear relationship between the two to make it significant.

Finally, Figure 14 presents the change in lighted area from 1992 to 2002 and further to 2012. Using Table 7 as guidance to interpret the map, it is clear that overall lighting decline can be seen in Moldova, Slovakia, Ukraine and the United Kingdom. Additionally, there is instability in parts of Spain, France, Germany and Bulgaria. These maps provide a clear visualization of the change in lighted area over time at a finer scale than the previous country level analyses; however, the findings are consistent between the two analyses.

In the case of lighting change, a regional division is not as apparent as with population change. There is no clear clustering of countries which experienced overall growth or decline in lighting. The three countries that experienced consistent decline both in lighted area and SOL are exclusively located in Eastern Europe. This indicates that decline is more prevalent in Eastern Europe than in Western Europe. However, caution must be taken in interpreting this conclusion as there are many other instances within the Eastern region where SOL and lighted area grew. Apart from the United Kingdom, the other countries that experienced overall decline experienced it only in SOL, where it was very minimal and where the year to year trend was one of stability. The United Kingdom is a unique country in that it saw decline in its SOL (although it was minimal and in fact attributed as stable in the typology) that cannot be attributed to instrument or measurement fluctuations. Therefore, in the United Kingdom, lighted area and SOL appear to be uncoupled.

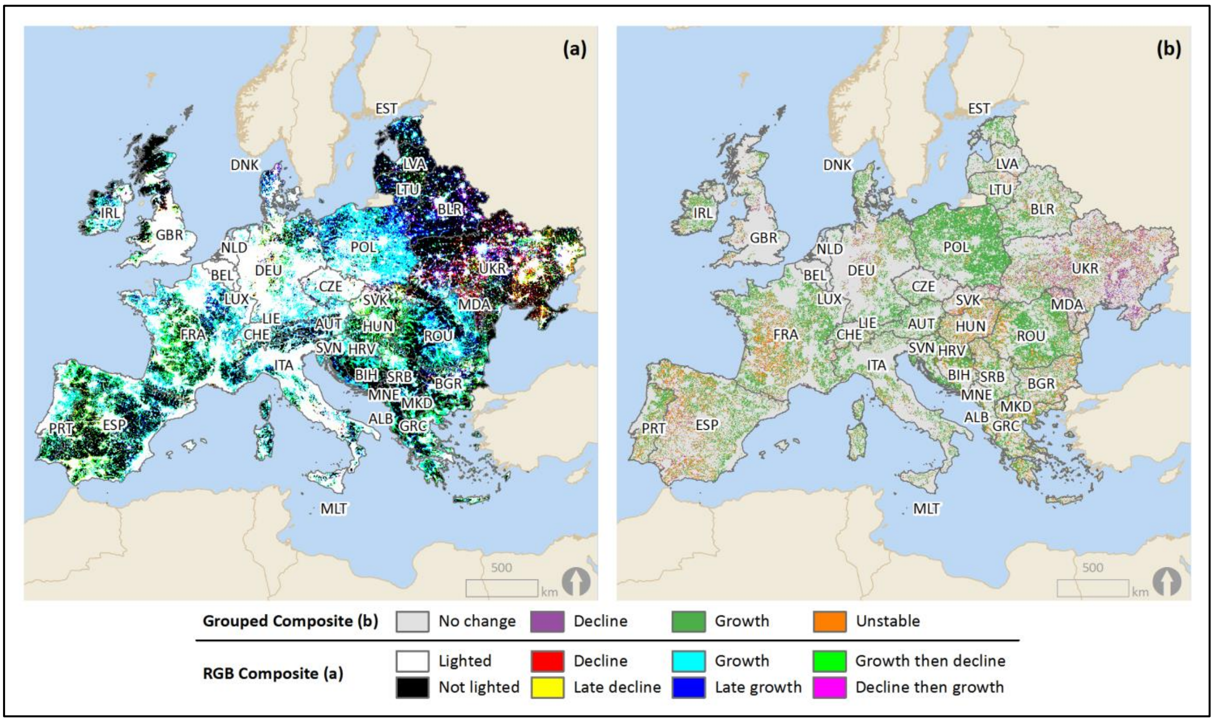


Figure 14. Pixel level lighted area change, 1992, 2002, 2012
(a) RGB composite for all eight types of change, (b) Composite grouped by major change pattern

4.2 Relationship between Population Change and Nighttime Lights

Having gained an overall understanding of the trends in lighting and population throughout Europe, the next step in the analysis was to look more closely at the relationship between the two. This section explores how population change and lighting change are related throughout Europe, examining regional and temporal differences.

4.2.1 Methods

The hypothesis for this section is built on an understanding of the relationship between the first demographic transition and human settlement patterns, as explored in Section 2.2.2. During the period of initial steep population growth and subsequent slowing in Europe, the extent of human development grew continuously. It is predicted that this growth in development will not be curbed by a reversal in population growth, at least not during the period of study. The SDT and accompanying demographic and economic trends do not provide evidence of a strong enough force to deter continued land development at this time.

To determine the relationship between population and light across Europe, the linear relationships between each country's population and each lighting indicator were calculated separately for each year. This served to provide a basic understanding of how SOL and lighted area are related to population throughout Europe.

The time series analysis was first incorporated by examining the overall change in population and lighting between 1992 and 2012. As was identified in the previous section, this type of measure hides mid-period fluctuations and is therefore not ideal. However, it does provide an accurate overview of patterns and was used here to identify the relationship between the change in population and the change in lighting over time. A quadrant graph of change was used to illustrate this for SOL and lighted area separately. Each country was plotted on the graph, where the horizontal axis represents the absolute change in population from 1992 to 2012 and the vertical axis represents the change in lighting. Similar calculations were done for the percent change per year; however these were not plotted on a graph. The resulting graph is composed of four quadrants which each represent a different relationship between population and light. These are presented in Figure 15.

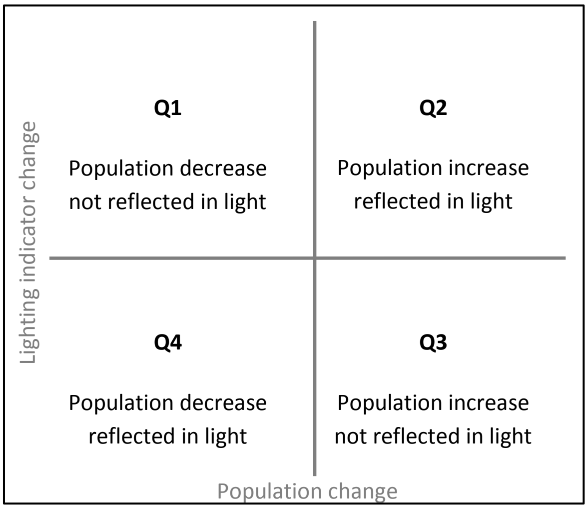


Figure 15. Population change v. nighttime lights quadrants

A further examination of the relationship between population and lighting was undertaken by examining the linear relationship between the two for each country in Europe over time. In some cases, the relationship is weak or insignificant because it is not actually linear. However, these correlations still provide a better picture of the time series relationship between population and light than the quadrant analysis because they incorporate data from every year rather than only the first and final years. Here, positive correlations reflect that population and lighting were coupled in their increase or decrease. Negative correlations reflect that they did not increase or decrease together. Instead, population increased while lighting decreased or vice versa. The value of the correlation indicates is strength, with values closer to one reflecting stronger tendencies towards linear association between the two variables. In order to calculate these time series correlations (as well as all other time series correlations calculated later) outliers were removed from the data. For the most part, the only outlier was from 2010, which, as noted earlier, had an uncharacteristically high SOL throughout Europe; however, in some countries it was 1992 which was an outlier.

This provided a general time series examination of the relationship between lighting change and population change within countries themselves. However, in order to examine the relationship more specifically for increasing and decreasing population periods, and to attempt to reduce the inaccuracies of non-linear correlations, the typologies developed in the previous section were used to subdivide each country's data into periods of population increase and population decrease. Countries with erratic populations were ignored for this part of the analysis. Each country was divided into at most two periods, one of increase and one of decrease. Those countries with steadily increasing or decreasing populations were not subdivided. The divisions resulted in a more clearly linear trend in population for each country since countries which did not exhibit linear population change were now divided into two periods of linear change. These linear change periods were then grouped together as either increasing or decreasing population periods. Table 10 presents these groups.

Table 10. Periods of increasing, decreasing and stable population change

Decreasing Population			Increasing Population			Stable Population		
Country	Year start	Year end	Country	Year start	Year end	Country	Year start	Year end
Albania	1992	2012	Austria	1992	2012	Italy	1992	2001
Belarus	1992	2012	Belgium	1992	2012	Slovakia	1992	2012
Bulgaria	1992	2012	Czech Republic	2002	2012			
Czech Republic	1992	2002	Denmark	1992	2012			
Estonia	1992	2012	France	1992	2012			
Germany	2003	2012	Germany	1992	2003			
Greece	2010	2012	Greece	1992	2010			
Hungary	1992	2012	Ireland	1992	2012			
Latvia	1992	2012	Italy	2001	2012			
Lithuania	1992	2012	Liechtenstein	1992	2012			
Macedonia, FYR	1992	1995	Luxembourg	1992	2012			
Montenegro	1992	2000	Macedonia, FYR	1995	2012			
Portugal	2010	2012	Malta	1992	2012			
Republic of Moldova	1992	2012	Montenegro	2000	2012			
Romania	1992	2012	Netherlands	1992	2012			
Serbia	1995	2012	Portugal	1992	2010			
Slovenia	1992	1998	Serbia	1992	1995			
Ukraine	1992	2012	Slovenia	1998	2012			
			Spain	1992	2012			
			Switzerland	1992	2012			
			United Kingdom	1992	2012			

The groups were used to examine the relationship between population and light more closely. The goal was to determine whether the relationship was significantly different for periods with increasing and decreasing populations. The correlation between population and each lighting indicator was therefore calculated separately for periods of population growth and decline. These correlations were interpreted in the same way as the correlations for lighting and population overall.

4.2.2 Results

The correlation between population and SOL ranges from 0.94 to 0.97. The average correlation is 0.96 (R^2 = 0.91). The average correlation between population and lighted area is 0.93 (R^2 = 0.87) and it ranges from 0.92 to 0.96. This shows that the correlation between light (both SOL and lighted area) and population in Europe has remained consistently strong over time. Basically, countries with a higher population tend to have a higher SOL and lighted area. An examination of Eastern and Western European countries separately reveals that there is no clear difference between them in terms of the relationship between population and the lighting indicator, as seen in Figure 16.

Figure 17 shows the population change relative to the change in nighttime lights. In general, most countries remain in the same quadrant for SOL and lighted area. The only exceptions are Belgium, Netherlands and the United Kingdom. Malta also cannot be placed in a quadrant for lighted area since it was completely lighted throughout the study period. Belgium and the Netherlands were two of the countries where SOL and lighted area did not have a significant relationship, so it is conceivable that the change in SOL and lighted area would not be consistent. The United Kingdom has a slightly increasing trend in lighted area and is located in Q2 but a clearly decreasing trend in SOL and is then located in Q3. This situation was also discussed in the previous section relating to the insignificant linear relationship between population and the lighting indicator and could reflect attempts to reduce light intensity and light pollution in the United Kingdom, although no evidence of such programs has been found.

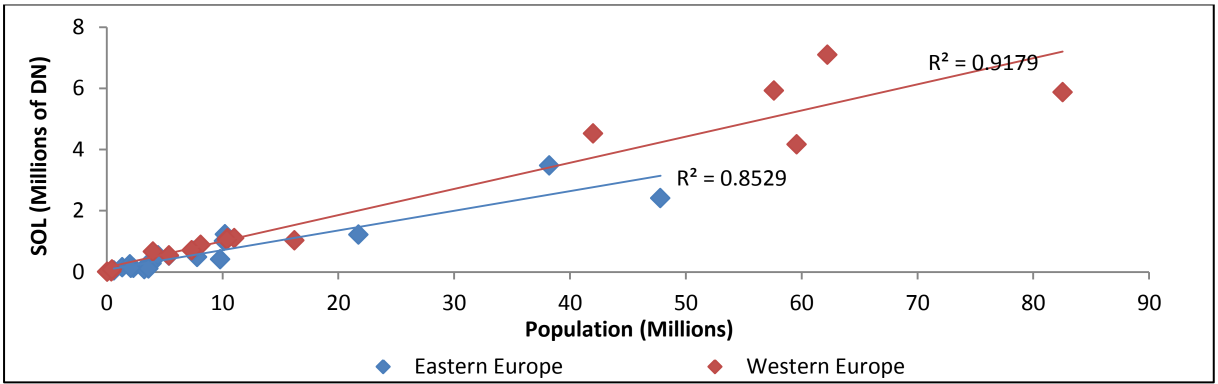


Figure 16. Correlation SOL v. population, 2002

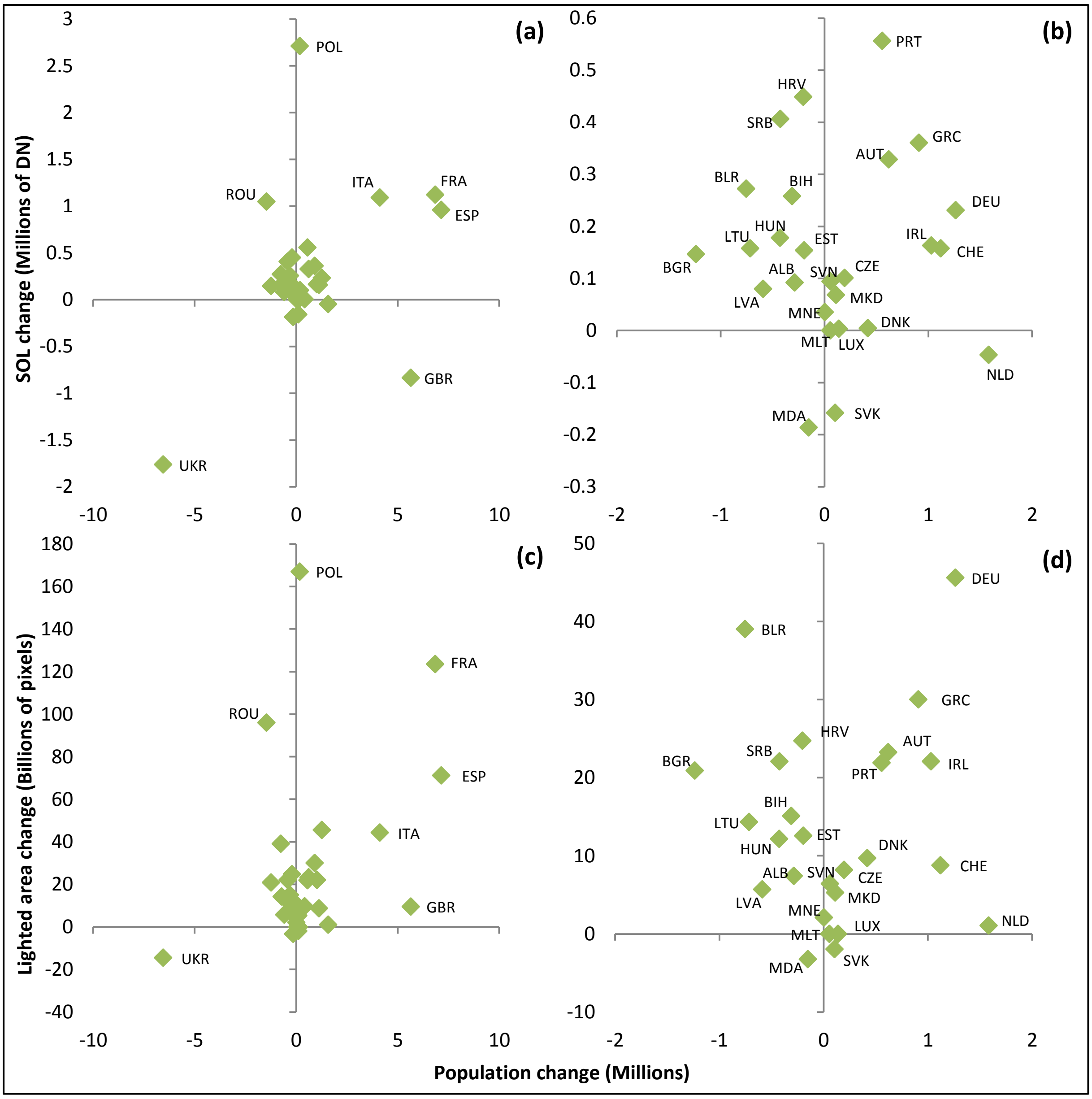


Figure 17. Change in population v. change in nighttime lights

(a) Change in SOL in all study countries, (b) Larger scale view of change in SOL for greater detail. Poland, Romania, Ukraine, Italy, France, Spain and United Kingdom removed, (c) Change in lighted area in all study countries, (d) Larger scale view of change in lighted area for greater detail. Poland, Romania, Ukraine, Italy, France, Spain and United Kingdom removed

Thirty-one percent of the countries in Europe are located in Q1 (population decrease and lighting increase) for both SOL and lighted area and all are in Eastern Europe. The population in all cases declined more slowly than the SOL or lighted area increased.

Forty-nine percent of countries are located in Q2 (population and lighting increase) for SOL and 57 percent for lighted area. For both, the countries in Q2 are for the most part in Western Europe, with the exception of Czech Republic, Poland, Montengro, Slovenia and Macedonia. For lighted area, there are three additional countries, Belgium, Netherlands and the United Kingdom in Q2 which are part of Q3 for SOL. In most countries, SOL and lighted area increased at higher rates than the population. Exceptions to this are Luxembourg for both SOL and lighted area, Denmark for SOL and Belgium, Netherlands and the United Kingdom for lighted area. Here nighttime lights increased at lower rates than population. In most of these countries, this is likely due to the fact that most of the country is lighted and has probably reached the DN saturation level. The discrepancy between the yearly population growth rate and the yearly growth in SOL and lighted area is more pronounced in Eastern Europe. In the Eastern European countries the yearly growth rate in lighting is on average 5 percent more than the yearly population growth rate, while in the Western European countries it is only 1 percent more.

Five countries (14 percent) are located in Q3 (population increase and lighting decrease) for SOL, while only one (3 percent) is in Q3 for lighted area. Slovakia is in Q3 for both SOL and lighted area, while four Western European countries are the remaining members of Q3 for SOL. SOL decreases in Malta, Belgium and Netherlands must, as has been noted, be taken with caution since these countries are fully (in the case of Malta) or almost fully lighted and the SOL could therefore be highly sensitive to the satellite calibration. As was noted, the United Kingdom is an interesting case in that it is in Q3 for SOL but in Q2 for lighted area. Slovakia, on the other hand, is found in Q3 for lighted area and SOL. This means that both the lighted area and SOL decreased. While this could be because of programs to reduce light intensity and development, it is likely that some other factor contributed to a decline in lighted area and that, because of this, the SOL decreased as well.

Two countries (6 percent) are located in Q4 (population and lighting decrease) for both SOL and lighted area. These are Ukraine and Moldova, both in Eastern Europe. The SOL declined more quickly than the population; however, the difference between the rates was not as great as when both SOL and population were increasing. In terms of lighted area, it decreased faster than the population decreased in Moldova, while in the Ukraine the opposite is true; however the difference in the rates is less than 1 percent. Therefore, in comparing the differences in the rates of change between countries where lighting and population decline together and where they increase together, it is clear that the rates are much closer when population and the lighting indicator decline together.

Figure 18 maps the spatial distribution of the quadrants in Europe. Here the spatial divisions can be seen most clearly. Population decreased in Eastern Europe (Q1, Q4); however lighting only followed in two countries (Q4). Other countries with decreasing lighting are spread throughout Europe, with no clear spatial pattern; however, these do not have decreasing populations (Q3). The most common trends are population and lighting growing together (Q2), as seen in Western Europe, or lighting growing and population declining (Q1), as in Eastern Europe. It is clear therefore, that in general lighting and population are not tied together over time. Lighting has, for the most part, followed an increasing trajectory throughout Europe, regardless of the change in population or the direction of its growth.

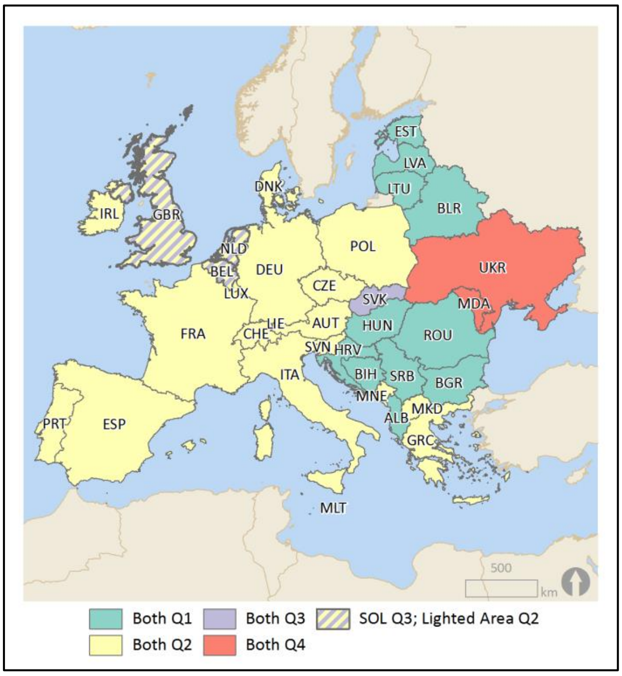


Figure 18. Population v. nighttime lights quadrants

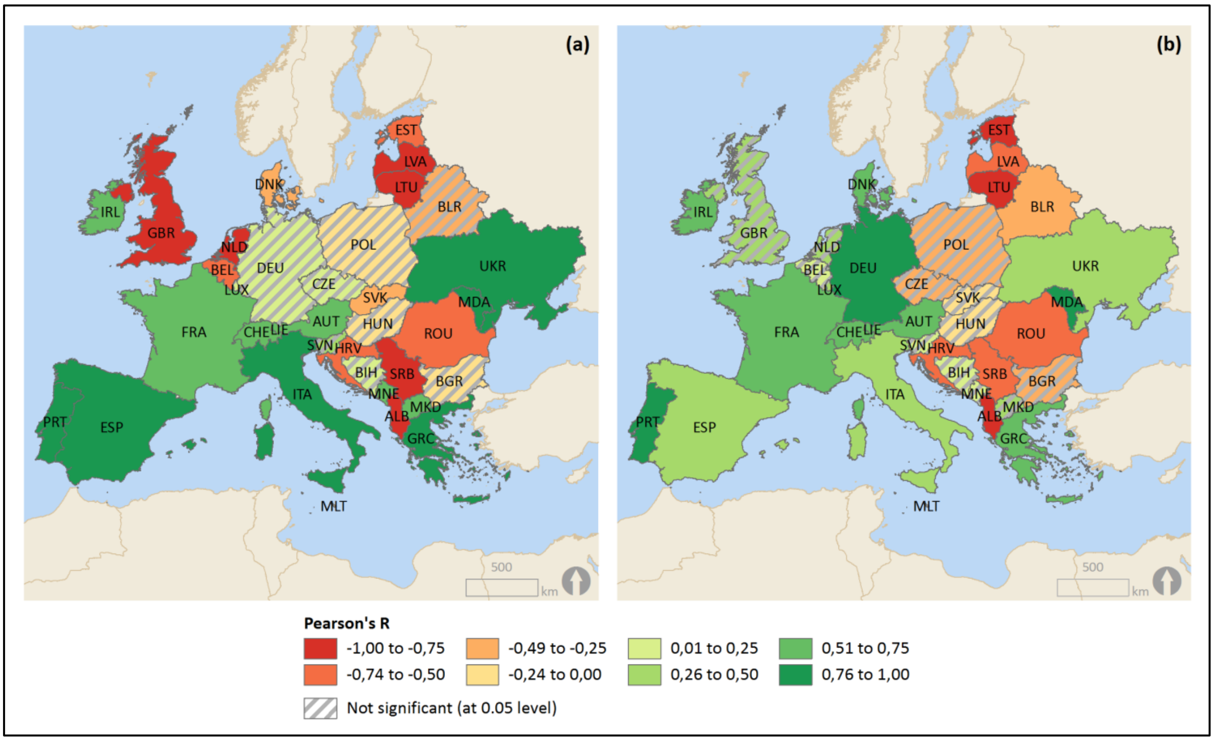


Figure 19. Correlation population v. nighttime lights
(a) Population v. SOL, (b) Population v. lighted area

To examine this more specifically, the correlations between population and each lighting indicator were examined and are presented in Table 11. Twenty-five, or 71 percent, of countries have significant correlations (at a 0.05 level) between the SOL and the population. Half are positive and half are negative. The average strength of the correlation is moderate (0.72). Similarly, 23 of 35 countries have significant correlations between lighted area and population. In this case, there are more positive correlations than negative correlations, with 61 percent being positive and 39 percent negative. The correlations are on average moderate (0.63) but weaker than with the SOL. As expected, the countries with negative correlations are consistent with those in Q1 and Q3 of the population change quadrants and those with positive correlation are consistent with Q2 and Q4 countries.

Figure 19 maps these correlations. It clearly indicates that the strength and direction of the correlation between population and light is varied throughout Europe. In some countries it is positive and in some it is negative and ranges from moderate to strong.

Table 11. Correlation population v. nighttime lights by country

	SOL		Lighted area	
Country	Pearson's R	R^2	Pearson's R	R^2
Albania	-0.95 ***	0.90	-0.84 ***	0.70
Austria	0.69 ***	0.48	0.66 ***	0.43
Belarus	-0.27	0.07	-0.47 **	0.22
Belgium	-0.70 ***	0.48	0.23	0.05
Bosnia and Herzegovina	0.14	0.02	0.11	0.01
Bulgaria	-0.24	0.06	-0.39 *	0.15
Croatia	-0.70 ***	0.49	-0.55 ***	0.31
Czech Republic	0.10	0.01	-0.30	0.09
Denmark	-0.48 **	0.23	0.52 **	0.27
Estonia	-0.63 ***	0.40	-0.76 ***	0.58
France	0.57 ***	0.32	0.54 **	0.29
Germany	0.05	0.00	0.89 ***	0.79
Greece	0.87 ***	0.76	0.69 ***	0.47
Hungary	-0.03	0.00	-0.10	0.01
Ireland	0.70 ***	0.49	0.66 ***	0.43
Italy	0.80 ***	0.63	0.44 **	0.19
Latvia	-0.76 ***	0.58	-0.75 ***	0.56
Liechtenstein	0.70 ***	0.49	0.80 ***	0.64
Lithuania	-0.76 ***	0.58	-0.77 ***	0.59
Luxembourg	0.11	0.01	0.39	0.15
Macedonia, FYR	0.50 **	0.25	0.44 *	0.20
Malta	-0.12	0.01	--	0.00
Montenegro	0.51 **	0.26	0.13	0.02
Netherlands	-0.79 ***	0.63	0.31	0.10
Poland	-0.23	0.06	-0.28	0.08
Portugal	0.98 ***	0.96	0.87 ***	0.75
Republic of Moldova	0.77 ***	0.60	0.77 ***	0.59
Romania	-0.71 ***	0.50	-0.51 **	0.26
Serbia	-0.84 ***	0.71	-0.55 ***	0.31
Slovakia	-0.48 **	0.23	-0.13	0.02
Slovenia	0.25	0.06	0.11	0.01
Spain	0.81 ***	0.65	0.49 **	0.24
Switzerland	0.62 ***	0.38	0.65 ***	0.42
Ukraine	0.82 ***	0.67	0.49 **	0.24
United Kingdom	-0.94 ***	0.89	0.36	0.13

* Significant at 0.1 level, ** 0.05 level, *** 0.01 level

However, these correlations serve to hide or weaken some of the relationships in countries where the population trajectory clearly changes. Therefore, correlations for periods of population increase and decrease were also calculated separately. These are presented in Table 12 and confirm that when population is increasing, the lighted area and population tend to have a positive correlation, while when population is decreasing, the tendency is for a negative correlation. Only in 23 percent of significant cases are population and lighted area coupled in decreasing populations (positive correlation), while they are coupled in 93 percent of cases in increasing populations. This shows that it is much more common for population and light to increase together than it is for them to decrease together. The relationship between population and SOL is similar. Again, population and SOL more commonly have a positive correlation when the population is increasing than when it is decreasing. In 73 percent of significant cases population and SOL increase together, while only in 18 percent of cases is change in SOL coupled with population decline. Therefore, while population and SOL tend to increase together, they do not tend to decrease together.

Table 12. Correlation population v. nighttime lights by period of population increase and decrease

	SOL		Lighted area	
Country	Pearson's R	R^2	Pearson's R	R^2
Periods of population decrease				
Albania	-0.95 ***	0.90	-0.84 ***	0.70
Belarus	-0.27	0.07	-0.47 **	0.22
Bulgaria	-0.24	0.06	-0.39 *	0.15
Czech Republic	-0.49	0.24	-0.60 *	0.36
Estonia	-0.63 ***	0.40	-0.76 ***	0.58
Germany	-0.45	0.21	0.69 **	0.48
Greece	0.66	0.44	0.84	0.70
Hungary	-0.03	0.00	-0.10	0.01
Latvia	-0.76 ***	0.58	-0.75 ***	0.56
Lithuania	-0.76 ***	0.58	-0.77 ***	0.59
Macedonia, FYR	-0.93 *	0.87	-0.93	0.86
Montenegro	-0.94 ***	0.87	-0.92 ***	0.85
Portugal	0.88	0.77	0.92	0.84
Republic of Moldova	0.77 ***	0.60	0.77 ***	0.59
Romania	-0.71 ***	0.50	-0.51 **	0.26
Serbia	-0.81 ***	0.66	-0.31	0.10
Slovenia	-0.91 ***	0.83	-0.82 **	0.67
Ukraine	0.82 ***	0.67	0.49 **	0.24
Periods of population increase				
Austria	0.69 ***	0.48	0.66 ***	0.43
Belgium	-0.70 ***	0.48	0.23	0.05
Czech Republic	0.27	0.07	-0.70 **	0.50
Denmark	-0.48 **	0.23	0.52 **	0.27
France	0.57 ***	0.32	0.54 **	0.29
Germany	0.50 *	0.25	0.93 ***	0.87
Greece	0.92 ***	0.85	0.78 ***	0.60
Ireland	0.70 ***	0.49	0.66 ***	0.43
Italy	0.72 ***	0.51	-0.30	0.09
Liechtenstein	0.70 ***	0.49	0.80 ***	0.64
Luxembourg	0.11	0.01	0.39	0.15
Macedonia, FYR	0.23	0.05	0.22	0.05
Malta	-0.12	0.01	--	--
Montenegro	0.78 ***	0.60	-0.08	0.01
Netherlands	-0.79 ***	0.63	0.31	0.10
Portugal	0.98 ***	0.96	0.89 ***	0.79
Serbia	0.61	0.37	0.95 *	0.89
Slovenia	0.06	0.00	-0.41	0.17
Spain	0.81 ***	0.65	0.49 **	0.24
Switzerland	0.62 ***	0.38	0.65 ***	0.42
United Kingdom	-0.94 ***	0.89	0.36	0.13

* Significant at 0.1 level, ** 0.05 level, *** 0.01 level

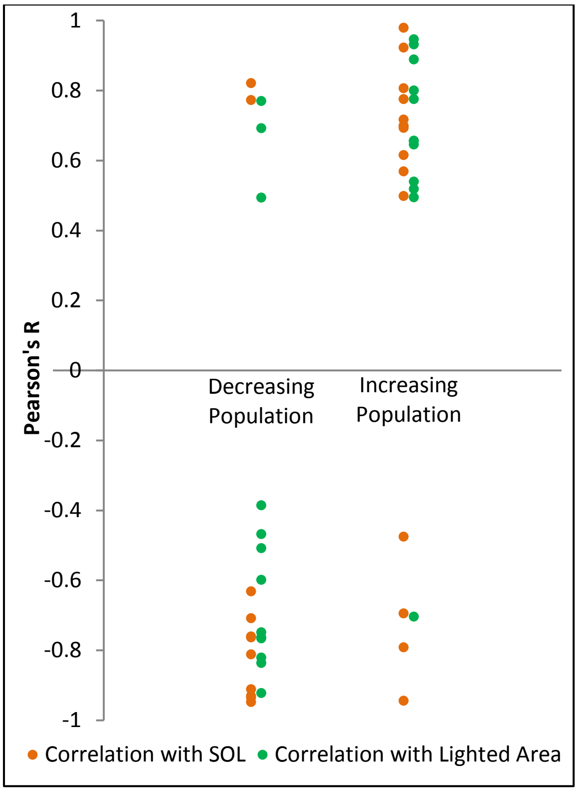


Figure 20. Comparison of correlation for periods of population increase and decrease

Figure 20 shows the significant correlations (at a 0.05 level) for periods of population decline and population increase plotted together. Here it can more clearly be seen that in increasing population periods, the tendency is for a positive correlation, or also increasing light while in decreasing periods, there are more negative correlations, or still increasing light. Basically, a pattern of continuously increasing light regardless of population can be seen. This is consistent with the previous findings regarding the overall change in light and the overall change in population. Population change does not appear to be coupled together with lighting change.

4.3 Relationship between Demographic Change and Nighttime Lights

The previous section illustrated the relationship between population and lighting throughout Europe. There is a strong relationship between the amount of light and the total population; however, the correlation weakens when examined on a country basis over time. Here, it is clear that the relationship is not consistent across Europe. The main finding is that despite changes in the population trajectory of a country, its lighting trajectory usually remains one of growth. This means that there must be other factors which impact lighting change over time. This section examines the relationship between demographic changes related to the SDT and lighting. This is done in order to establish whether these changes, which have accompanied population decline, might play a role in the continuing lighting increase. Apart from demographic changes, this section also briefly examines GDP as it relates to lighting change to determine if structural or economic factors play a stronger role in guiding lighting change over time than demographic factors do.

4.3.1 Methods

The following four demographic indicators were selected for analysis in this section: the percentage of the population over 64 years of age (O64), the percentage of the population under 15 years of age (U15), the percentage of people living in single person households (SPHH) and the average age at which young people permanently leave their parent's home (AYLH). For simplicity, each indicator will be referred to using its short form from this point forward. These variables were selected because they reflect some of the identified trends from the SDT and also because related data was freely available. Both U15 and O64 reflect the changing population age structure that has taken place during the SDT. SPHH reflects changing household structures, with a greater number of people living alone due to increase in divorce and late marriages. Similarly, AYLH also reflects changing household structures, as younger ages of leaving home indicate a potentially greater number of households. Finally, GDP was examined as a non-demographic variable which might still have a similar or greater impact on lighting change. GDP was selected based on the literature review which indicated a strong relationship between light and GDP in various studies.

The general hypothesis of this section is built on the idea that the trends in age structure and household composition should impact development through a differing demand for housing and therefore residential development and for other infrastructure as well which may be reflected in lighting extent and intensity. Overall, the hypothesis is that O64 and SPHH and lighting will be positively related. Accommodating an aging and increasingly independent population will mean that lighting continues to increase, regardless of whether population on the whole declines. On the contrary, U15 and AYLH will have a negative correlation with lighting. The relationship with the proportion of young people is a corollary to the relationship with the proportion of older population, while, as the age of people leaving home decreases, this increases the proportion of alternative household structures and the demand for space. The relationship with GDP is expected to be positive based on evidence from the literature review.

In order to compare the relationship between each of the selected indicators and each lighting indicator to the already established relationships with population, the correlation between each indicator and light was calculated as in the previous section. First, the linear relationship between each variable and each lighting indicator was determined. Second, these relationships were broken down by periods of population decline and population increase. Here, it is important to keep in mind that the division of countries into increasing and decreasing periods was based on their population change and not on any changes in the selected variable. The interpretation of such an analysis is therefore that if a variable is positively associated with lighting change consistently over the increasing and decreasing population periods, it can be said that this variable plays a role in lighting change since it means that, despite a change in the population trajectory, this variable and lighting are still coupled.

These relationships were graphically compared to the relationship between light and population in order to further understand how each variable affected each lighting indicator. The upper half of the graph shows periods where the selected variable and the lighting indicator were coupled. The bottom half of the graph reflects the opposite, that is, change in the variable was not tied to similar change in the lighting indicator. To the right of the vertical axis, the population and lighting indicator were coupled, while to the left they were not. Countries are located in the same place on the horizontal axis throughout the graphs and this location is based on the correlations calculated in the previous section. The relationship with the selected indicator, which is depicted on the vertical axis, is what changes. If most observations are found in the upper half of the graph, it can be said that an indicator contributes positively to lighting change regardless of population change and that therefore change in this indicator does impact lighting more than population change does.

4.3.2 Results

Table 13 presents the correlations between each selected indicator and SOL and lighted area respectively for each country. For SOL, the relationship is significant (at a 0.1 level) in 69, 76, 68, 42, and 46 percent of cases where data was available for GDP, O64, U15, SPHH and AYLH respectively. For lighted area 74 percent, of the correlations are significant for each of GDP, O64 and U15 and 35 percent and 19 percent are for SPHH and AYLH respectively. The low level of significant correlations with SPHH and AYLH is mainly a reflection of the small sample size (in many cases less than 15). It could, however, also reflect a weak linear relationship between the two variables and lighting. In order to better understand this relationship, larger sample sizes would be required. It is therefore important to keep in mind the small sample size and therefore weak associations when examining SPHH and AYLH and to take the findings regarding these two variables cautiously. The following analysis is for those countries that had significant correlations between the selected variable and the lighting indicators.

In general, the variables are all better at explaining the variation in the SOL than in the lighted area. The average strength of the correlations ranges from 0.54 for SPHH and lighted area to 0.74 for O64 and SOL, which reflect moderate correlations. O64 and U15 have the strongest correlations, while SPHH has the weakest. In terms of the direction of the correlations, as hypothesized, GDP, O64 and SPHH all share a greater number of positive correlations while U15 and AYLH have a greater number of negative correlations. This shows that the tendency is for GDP, O64 and SPHH to be coupled in lighting growth or decline over time in a greater proportion of countries, while lighting grows or declines in the opposite direction of U15 and AYLH more commonly.

Figure 21 shows the comparison between the correlations for each lighting indicator and each selected variable against the correlation between the lighting indicator and population. The previous section examined the relationship between lighting and population and found that population decrease is not tied to lighting decrease in the same way that population increase is tied to lighting increase. These figures demonstrate which variables are more directly tied together with lighting change.

Regardless of whether populations are increasing or decreasing, the SOL and O64 have a tendency to have a positive correlation. The strength of this positive relationship ranges from 0.55 to 0.99 (at a 0.1 significance level), but averages 0.75. The case is similar between lighted area and O64, although the correlations are slightly stronger. In both cases, this shows that O64 serves as an explanatory factor for lighting change. This is not to say that there are no outliers to these trends. Looking at the relationship between lighted area and O64, as seen in Figure 21, outliers can be seen in the bottom half of the graph. Three countries, Germany, Ukraine and Moldova, during the period of population decrease are clear outliers from the overall trend of positive correlations between lighted area and O64 (all at 0.1 significance level). Coupled with the fact that these countries are also outliers in their relationship between lighted area and population, this may reflect that there are other variables at work in driving the lighted area down. Similarly, both Ukraine and Moldova are also outliers with regards to SOL. In terms of periods of population increase, Ireland and Czech Republic are outliers with regards to lighted area and Belgium, Netherlands, the United Kingdom and Ireland with regards to SOL.

Table 13. Correlation indicators v. nighttime lights by country

	GDP		O64		U15		SPHH		AYLH	
Country	SOL	Lighted area	SOL	Lighted area	SOL	Lighted area	SOL	Lighted area	SOL	Lighted area
Albania	0.92 ***	0.75 ***	0.90 ***	0.73 ***	-0.89 ***	-0.70 ***	nd	nd	nd	nd
Austria	0.72 ***	0.78 ***	0.65 ***	0.48 **	-0.68 ***	-0.62 ***	0.49 **	0.51 **	0.49	-0.18
Belarus	0.47 **	0.54 **	-0.13	0.26	0.66 ***	-0.25	nd	nd	nd	nd
Belgium	-0.51 **	0.68 ***	-0.60 ***	0.83 ***	0.51 **	-0.62 ***	-0.56 **	0.24	-0.01	0.02
Bosnia and Herzegovina	0.86 ***	0.67 ***	0.83 ***	0.69 ***	-0.59 **	-0.67 ***	nd	nd	nd	nd
Bulgaria	0.30	0.30	0.21	0.25	-0.16	-0.38	0.08	-0.52	0.55	-0.54
Croatia	0.78 ***	0.68 ***	0.92 ***	0.83 ***	-0.92 ***	-0.77 ***	-0.74	0.36	0.68 **	-0.18
Czech Republic	-0.02	0.34	0.14	0.30	-0.09	-0.31	-0.40	-0.47	-0.35	-0.47
Denmark	-0.48 **	0.66 ***	0.08	0.02	-0.30	0.60 ***	0.24	-0.57 *	0.95	0.82
Estonia	0.41 *	0.65 ***	0.63 ***	0.79 ***	-0.52 **	-0.74 ***	0.74 ***	0.60 **	-0.62 **	-0.50 *
France	0.63 ***	0.66 ***	0.67 ***	0.61 ***	-0.65 ***	-0.62 ***	0.26	0.18	-0.67 **	0.54
Germany	0.07	0.65 ***	0.05	0.52 **	0.29	-0.44 *	-0.69 ***	0.24	0.20	0.00
Greece	0.85 ***	0.69 ***	0.88 ***	0.70 ***	-0.28	-0.07	0.35	-0.03	-0.57 *	-0.31
Hungary	0.04	0.21	0.03	0.06	-0.15	-0.24	-0.67 **	-0.23	-0.59 **	-0.81 ***
Ireland	0.13	0.14	-0.58 ***	-0.67 ***	-0.88 ***	-0.95 ***	0.60 **	0.43 *	-0.43	-0.29
Italy	0.83 ***	0.87 ***	0.93 ***	0.79 ***	-0.90 ***	-0.90 ***	0.77 ***	0.32	-0.70 **	0.65 *
Latvia	0.33	0.53 **	0.55 **	0.66 ***	-0.43 *	-0.65 ***	0.48	0.37	0.04	-0.20
Liechtenstein	0.59 **	0.84 ***	nd	nd	nd	nd	nd	nd	nd	nd
Lithuania	0.42 *	0.45 *	0.50 **	0.67 ***	-0.49 **	-0.55 **	0.84 ***	0.64 **	-0.56 *	0.10
Luxembourg	0.01	0.68 ***	-0.01	0.70 ***	0.06	0.23	-0.25	0.59 ***	-0.56 **	-0.13
Macedonia, FYR	0.10	0.00	0.39 *	0.34	-0.25	-0.17	nd	nd	0.59	-0.78 **
Malta	-0.12	--	-0.18	--	0.14	--	0.09	--	-0.15	--
Montenegro	0.78 ***	0.18	0.88 ***	0.90 ***	-0.94 ***	-0.87 ***	nd	nd	nd	nd
Netherlands	-0.47 **	0.33	-0.65 ***	0.32	0.11	0.16	-0.38	0.14	-0.37	-0.24
Poland	0.77 ***	0.76 ***	0.77 ***	0.85 ***	-0.75 ***	-0.69 ***	0.33	0.21	-0.66 **	-0.20
Portugal	0.95 ***	0.92 ***	0.98 ***	0.82 ***	-0.96 ***	-0.89 ***	0.88 ***	0.56 **	0.76 ***	-0.14
Republic of Moldova	0.11	-0.26	-0.82 ***	-0.78 ***	0.31	0.76 ***	nd	nd	nd	nd
Romania	0.58 ***	0.43 *	0.77 ***	0.78 ***	-0.75 ***	-0.55 **	0.59 *	0.00	0.62 **	-0.18
Serbia	0.73 ***	0.39 *	0.85 ***	0.85 ***	-0.88 ***	-0.68 ***	nd	nd	nd	nd
Slovakia	-0.79 ***	-0.56 ***	-0.70 ***	-0.47 **	0.76 ***	0.37 *	-0.16	0.21	-0.30	-0.87 ***
Slovenia	0.52 **	0.58 ***	0.58 ***	0.58 ***	-0.64 ***	-0.43 *	0.21	-0.26	-0.35	0.11
Spain	0.90 ***	0.71 ***	0.91 ***	0.83 ***	-0.89 ***	-0.71 ***	0.79 ***	0.44 *	-0.7 ***	0.14
Switzerland	0.61 ***	0.71 ***	0.61 ***	0.64 ***	-0.50 **	-0.52 **	-0.14	-0.67	nd	nd
Ukraine	0.00	-0.45 **	-0.82 ***	-0.46 **	0.85 ***	0.47 **	nd	nd	nd	nd
United Kingdom	-0.78 ***	0.66 ***	-0.69 ***	0.02	0.79 ***	-0.48 **	0.23	0.53 **	-0.28	-0.30

* Significant at 0.1 level, ** 0.05 level, *** 0.01 level   nd = No data available

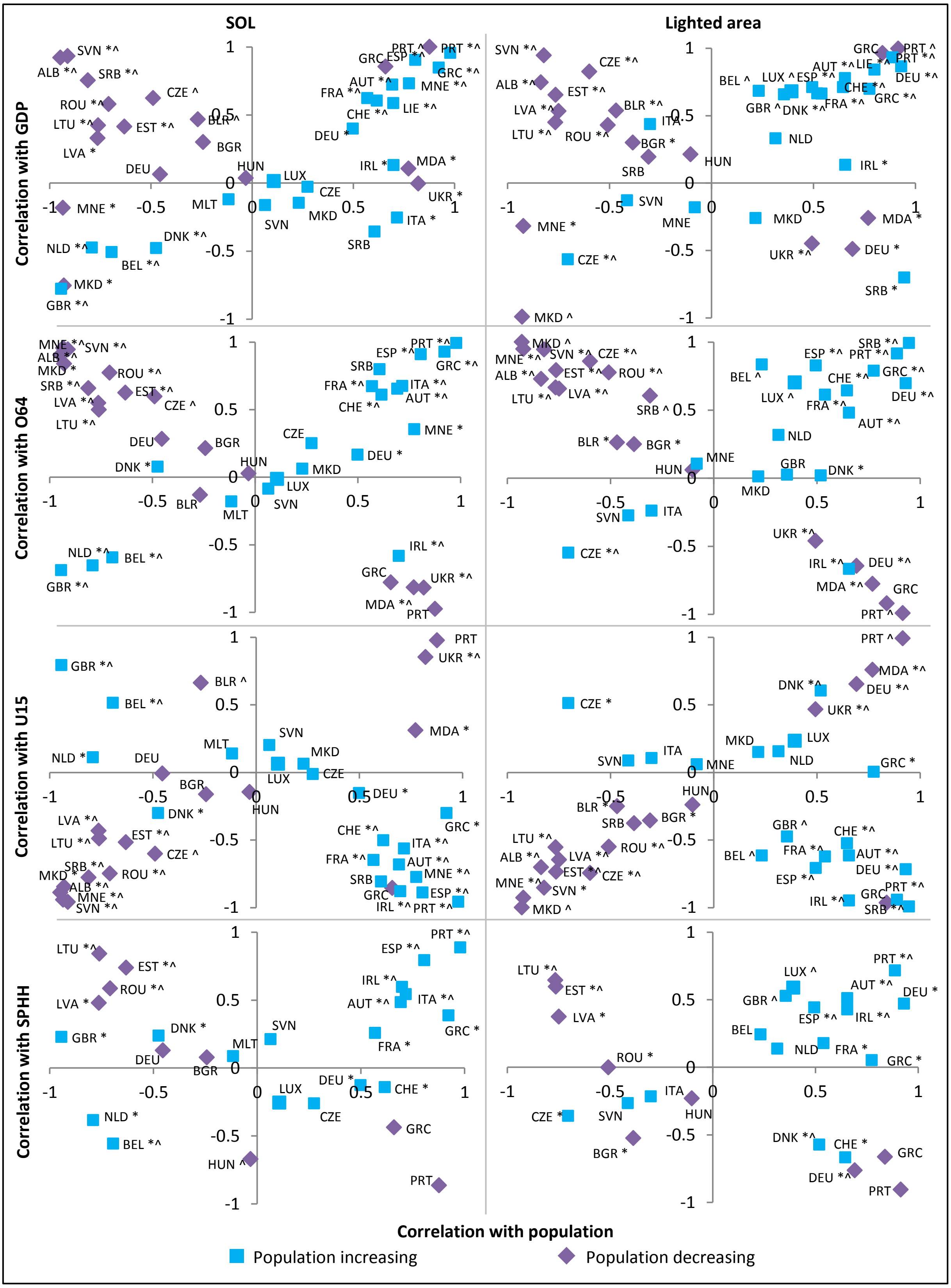


Figure 21. Correlation comparison indicators and population v. nighttime lights

* Denotes that the correlation with population is significant at 0.1 level

^ Denotes that the correlation with the indicators is significant at 0.1 level

The results in regards to U15 are similar to those of O64. Regardless of whether populations are increasing or decreasing, the SOL and U15 have a tendency to have a consistent correlation; however, in this case it is a negative correlation. The strength of the relationship ranges from -0.43 to -0.97 (at a 0.1 significance level), but averages -0.72, which is also a moderate relationship. Again, the relationship with lighted area is similar. Here, the majority of countries have a negative relationship, regardless of whether population is increasing or decreasing. The strength of the relationship is again -0.72 on average, ranging from -0.55 to -0.99. In both cases, this shows that U15, like O64, serves as an explanatory factor for lighting change. Regardless of the population trajectory, the light indicator moves in the opposite direction of U15. When there are a higher proportion of children in the population, the lighting indicator decreases, while when there are a lower proportion of children in the population, the lighting indicator increases. This is consistent with the findings for O64.

With SPHH there are very few significant correlations when divided into periods of population decline and population increase. Still, examining all the correlations as seen in Figure 21 there is a tendency for positive correlations; however, there is less of a division between positive and negative correlations with SPHH than there was with O64 and U15. In some countries, SPHH has a positive correlation with light and in others a negative correlation (both SOL and lighted area). Unfortunately, due to lack of strong data to examine this variable, the results are deemed to be inconclusive. Likewise, observations from AYLH are inconclusive because there are even fewer significant correlations.

GDP is the last variable to be examined, as it is not a demographic variable and is predicted to work separately from the demographic variables in influencing lighting change over time. The trends in the correlation between GDP and each lighting indicator are similar to those between O64 and U15 and the lighting indicators. Regardless of whether populations are increasing or decreasing, the lighting indicators and GDP tend to have a positive correlation. Both the negative and positive correlations are moderate to strong. Specifically, the positive correlations range from 0.41 to 0.99 for SOL and 0.43 to 0.99 for lighted area, with an average of 0.71 for both SOL and lighted area. In general, GDP does not explain more of the variation in SOL or lighted area than do O64 or U15. The same outliers seen between lighted area and O64 and U15 are seen with GDP; however, only the relationship in Ukraine is significant in this case. More notably, there are four outliers in the relationship between SOL and GDP and population. Belgium, Netherlands, Denmark and the United Kingdom have a significant negative correlation between GDP and SOL as well as, as was previously examined, between population and SOL. As already explained, sensitivity of the sensor to changes in lighting in these countries, as well as their overall stability in lighting change could have contributed to these outlying relationships.

In general, the strength of the relationship between each lighting indicator and each variable is similar to the strength of the relationship between each lighting indicator and population for each country, as evidenced by the strong diagonal axes seen in each of the graphs. The major difference lies in the overall strength of the relationships. For some countries, such as Portugal, Albania and Serbia, the observed relationships are continuously strong, located in the outer corners of the graphs. For others, such as Hungary and Bulgaria, they are consistently weak and not significant.

Chapter 5: Discussion and Conclusions

5.1 Discussion

The results confirm that European countries are indeed experiencing population decline. Regional differences in the extent and timing of population decline exist between Eastern and Western Europe. However, the results show that these population declines are not reflected in SOL or in lighted area. Instead, there is a tendency throughout Europe for SOL and lighted area to be uncoupled from population change. This is especially evident in Eastern Europe, where population decline has not been consistently tied to decline in SOL or lighted area. Results of the correlation between other demographic variables and SOL and lighted area displayed varying relationships. The relationships with O64 and U15 both suggest that the changes in age structure that have accompanied changes in population could be a driving force behind the discrepancy between population change and lighting change. The relationships with SPHH and AYLH are less conclusive because of small sample sizes. Results of the correlation with GDP mimic those of O64 and U15; consistently increasing GDP during times of population change may be an explanatory factor in the lack of a coupled relationship between population and light.

The examination of population over time confirms that population decline started in Eastern Europe even before 1992 and, for the most part, continued consistently throughout the study period. Only in Czech Republic, Montenegro, Slovenia and Macedonia has there been a reversal in population decline. In these countries, a low rate of population decrease has been followed by a low rate of population increase (less than 0.5 percent). In Western Europe, the major trend has been towards steady population growth; however, in Germany, Greece and Portugal, population decline set in after 2000. It remains to be seen whether these reversals in population change will continue or whether they are temporary fluctuations in the population trajectories of these European countries. However, according to the UN World Population Prospects (2012, medium variant) most European countries will start to experience population decline before 2050 and Europe's population as a whole will start to decline sometime between 2015 and 2020 (UN DESA, 2013a). Therefore, while it is possible that the population reversals in Germany, Greece and Portugal are indeed temporary, it is far more likely that they are ushering in the beginning of population decline in Western Europe and that other Western European countries will soon follow.

The examination of lighting change over time reveals that regional divisions are not as clear as those seen in population change over time. The distribution of lighting increase and decrease shows no clear clustering (Figure 12). Only three countries, Slovakia, Moldova and Ukraine experienced overall declines in lighted area. Seven countries, including Belgium, Netherlands, Malta, the United Kingdom, Slovakia, Moldova and the Ukraine, experienced overall declines in SOL. The declines in SOL in Belgium, Netherlands and Malta have been dismissed throughout the study as a reflection of the instability of the satellite sensors. The small size of these countries, coupled with the fact that they are almost entirely lighted and highly urban, means that any slight variations in the sensors impact the SOL greatly. The United Kingdom saw growth in lighted area alongside a decline in the SOL, which could reflect continuous expansion and development tied with more conservative use of lighting. However, no evidence of government run programs to promote such energy conservation has been found. Only Slovakia, Moldova and the Ukraine experienced consistent lighting decline over the study period. While these three countries are all located in Eastern Europe, it cannot be concluded that Eastern Europe is experiencing lighting decline since there are many other Eastern European countries that experienced lighting growth; however, it could be said that lighting decline is more likely to occur in Eastern Europe that in Western Europe, although such a conclusion would be based more in an understanding of the differences in the political, economic and development pasts between Eastern and Western Europe than it would be in the spatial distribution of the results. The results of the relationship between population and lighting reveal that there is a strong, positive relationship between both SOL and population and lighted area and population across Europe on a yearly basis. This finding is consistent with previous findings identified through the literature review (Pozzi , Small and Yetman, 2002; Sutton, et al., 2001; Elvidge, et al., 1997). It could be said to also be an obvious link. Countries with higher populations use more light both in terms of intensity and in terms of developed area because they are accommodating a greater number of people. However, it is interesting to note that the relationship holds even for countries with limited space, such as Malta or the Netherlands.

However, this strong relationship between population and light does not hold when examined over time for each country separately. In this case, the results show that some countries have a positive relationship between light and population, while others have a negative relationship. Examining the correlations for periods of increasing and decreasing population separately reveals a pattern in the direction of the correlation. When the direction of population growth is controlled for, the results display a moderate to strong positive correlation with light when population is growing; however, when population is decreasing, the correlation becomes negative, but is generally equally as strong or stronger. The results therefore show that lighting and population change tend to be coupled only when population is growing, but that they tend to become uncoupled when population is declining. The only cases when population decline is tied to lighting decline consistently for the entire study period are in Ukraine and Moldova. Apart from this, Germany is the only other country where a period of population decline is tied together with lighting decline, and then only in terms of lighted area (at a significance level of 0.05). This provides further evidence that regardless of the change in the population trajectory, lighting continues on its path of growth.

The findings on the relationship between other demographic variables and lighting and between GDP and lighting are summarized in Figure 22. On the one hand both O64 and GDP are consistently coupled with lighting, regardless of changes in the population trajectory. Although exceptions exist where these variables and lighting are not coupled, the general trend is one of a positive and moderate linear relationship. It can therefore be concluded that the proportion of the population that is over the age of 64 as well as a country's GDP may positively influence both SOL and lighted area over time. On the other hand, but connected to this, the relationship with U15 is predominantly a negative relationship. Therefore, the proportion of a country's population that is under 15 years of age has a negative association with lighting, that is, the fewer young people in a population, the greater the SOL and lighted area. This is obviously complimentary to the findings regarding O64, as declines in the proportion of young people will be reflected in increases in the proportions of middle aged and older people.

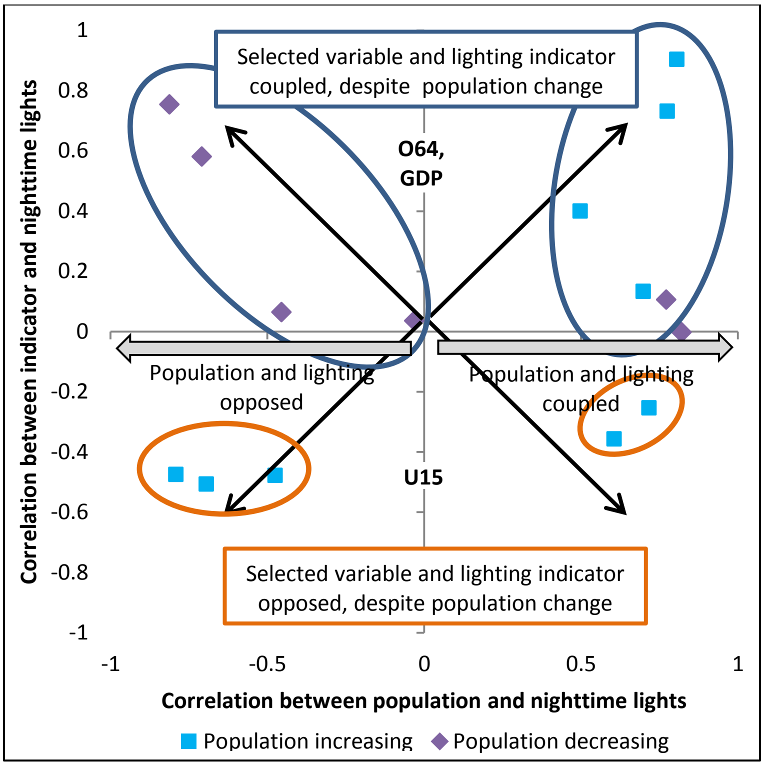


Figure 22. Summary of correlation comparison findings

The findings on GDP are consistent with other studies (Chen and Nordhaus, 2011; Ghosh, et al., 2010; Doll, Muller and Morley, 2006; Elvidge, et al., 1997) which find that GDP is related to lighting, although most of these studies have not examined the relationship over time. The findings regarding the age structure of the population are, to the extent of the literature review, new. These reflect how the SDT in general, and not just population decline, are influencing lighting trends in Europe. While population decline and lighting are not coupled, it is clear that there is a relationship between the age structure of the population and lighting change. An aging population which is a trend that accompanies Europe's population decline according to the SDT theory may contribute to continued lighting growth in that it encourages continued need for development along the same lines as a population with a larger proportion of middle aged people. While young people tend to be coupled with their parents in housing, spending, transportation and general use of infrastructure, the older generation tends to have greater independence from the middle aged population and therefore require separate housing and infrastructure and generally access the economy separately. This may lead to a continued demand for development in populations where the proportion of people over 64 is rising, even if the overall population is declining. If population decline is driven by a reduction in the number of births, as is the case in Europe, based on evidence from UN DESA (2013a) and from the SDT theory, then demand for development and infrastructure may not decline as quickly as population, since the young population may have a lower demand for development. A possible hypothesis, therefore, is that there may be a lag between population decline and lighting decline; however, there was no evidence of this during the current study period and further study would be required to develop this hypothesis.

Unfortunately, the results regarding SPHH and AYLH were inconclusive due to a lack of data over the entire study period and for all study countries. With SPHH the results showed a tendency towards moderate positive correlations, similar to with O64 and GDP; however, not enough of these correlations were significant (at even a 0.1 significance level) to draw similar conclusions to those drawn for O64 and GDP. With AYLH even fewer significant correlations were found. This could reflect that the relationship between light and each of these variables is in fact not linear; however, it is more likely a reflection of the limited sample sizes. Therefore, future directions for research may include further analyses regarding the relationship between light and household composition as well as other trends which make up the SDT.

In summary, the results suggest that SOL and lighted area are related to the size of the population throughout Europe; however, they suggest that, over time, declines in population are not commonly reflected in SOL and lighted area. Instead, SOL and lighted area appear to be more closely tied to GDP and to the population age structure. If SOL and lighted area are taken as indicators of physical development, as is suggested in previous studies, then there appears to be a separation between the overall size of a population and the demand for development over time. Demand for development appears to be more closely tied to the age structure of the population as well as to the economic development of European countries. These findings suggest that population decline alone will therefore not be a means to reduce the human footprint on the Earth. In fact, if the SDT theory is indicative of the trends which will accompany population declines, these results suggest that continued growth in development can be expected in Europe despite population declines.

5.2 Conclusions

The aim of this thesis was to detail the relationship between population and nighttime lights with regards to population decline in Europe, using time series analysis. Specifically, three key questions were asked. First, how population and nighttime lights changed during the study period? Second, what the relationship between population and nighttime lights was and how population decline was reflected in nighttime lights? And third, if other demographic developments related to the SDT influenced nighttime lights? The following are the main findings relating to these questions.

Population has been declining in Eastern Europe since before 1992 and decline in Western Europe begun to set in as early as 2000.
While not all Eastern European countries experienced steady population declines during the study period, the major tendency in the region was towards population decline or erratic population change. On the contrary, the major trend in Western Europe was one of steady population growth, with the exception of three countries where population growth peaked sometime after 2000 and steady population decline set it. It remains to be seen if population decline in these countries will continue and if other Western European countries will follow.

SOL and lighted area have been growing in most countries in Europe with the exception of Ukraine, Moldova, Slovakia and the UK.
Lighted area usually grew at a faster pace than did SOL; however, for the most part, both grew consistently during the study period. More countries experienced a decline in SOL than in lighted area. Many countries in Western Europe experienced stable lighting change during the study period. Additionally, changes in Belgium, Netherlands, Malta and Luxembourg were discounted throughout the study as reflections of measurement error and the saturation of DN values.

In Europe as a whole there is a positive association between nighttime lights and population.
On a year to year basis, countries with a high population tend to have a high SOL and lighted area as compared to countries with a low population, which tend to have a lower SOL and lighted area. This is consistent with the findings of previous studies.

During periods of population increase, nighttime lights and population are coupled; however, during periods of population decrease they are not.
In a time series view, the majority tendency for countries experiencing population increase is for a positive and moderate relationship between population and nighttime lights (both SOL and lighted area). During periods of population decline, this relationship remains moderate but reverses to a negative association, indicating that population and nighttime lights are not coupled in both their increase and decrease. This reflects that nighttime lights, and by extension, human development activity, were not directly tied to population change during the study period.

O64, U15 and GDP share a consistent relationship with nighttime lights during both periods of population increase and population decrease.
Despite the opposition of nighttime lights and population change during periods of population decline, nighttime lights are still positively associated with O64 and GDP throughout the study period. On the flip side, U15 is consistently negatively associated with nighttime lights. This suggests that both the change in the age structure of the population and the country's economic development impact nighttime lights to a greater extent than population change. Characteristics of the SDT which accompany population decline may therefore play a role in the continued growth of human development activity despite population declines.

In summary, while population change and change in the extent of human development may have been linked during the first demographic transition, it now appears that this linkage will not continue through the SDT. Instead, nighttime light change has been shown to be independent from population decline.

5.3 Directions for future research

First, while preliminary associations between other demographic data and nighttime lights in relation to population decline have been explored, conclusions regarding SPHH and AYLH were not significant and could be explored further.

Second, exploring the possibility of leads and lags in nighttime lights change following population change could add additional understanding to the relationship between nighttime lights and population. While the current 21 year study period is relatively short in order to examine such links, when additional data becomes available, such research may be undertaken. It is possible that population change will in fact be reflected in nighttime lights with some delay.

Third, and related to the idea that nighttime lights change may lag behind population change, is the idea that population change may in fact affect the rate of change of nighttime lights. While absolute decline in nighttime lights does not match decline in population, it is possible that population decline leads to a slowing of nighttime light growth. For this reason, future research could explore the relationship between population decline and the rate of change in nighttime lights.

Finally, examining the patterns identified at a smaller scale may reveal more information as to the nature of the relationship between population decline and nighttime lights. Recently, research regarding the effect of population decline on urban areas has been growing, and it may be interesting to link such research to the present study. Further study into whether population decline in cities is reflected in nighttime lights could be relevant. Particularly, an understanding on how development in cities declines, fractures, or fragments may be important. However, the DMSP-OLS dataset is limited for use in this respect because of the fact that it saturates at high DN values. It is therefore difficult to undertake the within-city analysis which would be required for this type of study.

The NOAA-NGDC's current focus is on a second nighttime lights dataset, the Visible Infrared Radiometer Suit (VIIRS), which improves on the spatial resolution, radiometric calibration and usable dynamic range of the DMSP-OLS dataset and may therefore provide an avenue for such city-level study (Elvidge, et al., 2013). Additionally, use of such a dataset may reduce some of the measurement issues identified throughout the present study.

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