REPORT

Nighttime lights and population changes in Europe 1992–2012

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Abstract Nighttime satellite photographs of Earth reveal the location of lighting and provide a unique view of the extent of human settlement. Nighttime lights have been shown to correlate with economic development and population but little research has been done on the link between nighttime lights and population change over time. We explore whether population decline is coupled with decline in lighted area and how the age structure of the population and GDP are reflected in nighttime lights. We examine Europe between the period of 1992 and 2012 using a Geographic Information System and regression analysis. The results suggest that population decline is not coupled with decline in lighted area. Instead, human settlement extent is more closely related to the age structure of the population and to GDP. We conclude that declining populations will not necessarily lead to reductions in the extent of land development.

Keywords Nighttime lights · Demographic transition · Population decline · Human settlement extent

INTRODUCTION

The distribution of artificial lighting on Earth, best observed from space at night, provides a unique view of human settlement, density, and distribution (Chen and Nordhaus 2011; Levin and Duke 2012). Such observations of lighting are known as nighttime lights imagery and are gathered by satellites that photograph the Earth at night. The potential of nighttime light data to be used as an inventory of human settlement was identified in the 1980s (Elvidge et al. 1997). Although still not a well-used dataset within the social sciences, nighttime light data have been used in research related to economic development (Elvidge

et al. 1997; Doll et al. 2006; Ghosh et al. 2010; Chen and Nordhaus 2011; Henderson et al. 2012), population (Sutton 1997; Elvidge et al. 1997; Sutton et al. 1997, 2001; Pozzi et al. 2002; Doll 2010a), urbanization (Imhoff et al. 1997; Henderson et al. 2003; Small et al. 2005; Elvidge et al. 2007), epidemiology (Kloog et al. 2008; Bharti et al. 2011), wars and crime (Agnew et al. 2008; Witmer and O'Loughlin 2011), and poverty (Moor et al. 2008; Elvidge et al. 2009; Doll and Pachauri 2010).

Links between the extent of lighted area and population counts, population density, and population distribution have been established by various researchers (Sutton 1997; Elvidge et al. 1997; Sutton et al. 1997, 2001; Pozzi et al. 2002). Likewise, nighttime lights have been shown to share a strong relationship with human economic activity (Elvidge et al. 1997; Doll et al. 2006; Chen and Nordhaus 2011; Henderson et al. 2012).

The objective of this article is to use nighttime lights as a measure of human settlement extent to evaluate the question of whether population decline is coupled with decline in the extent of human settlement or whether human settlement continues to expand despite declines in population.

We study population and lighting change between 1992 and 2012, a period which was selected based on the availability of nighttime light data. We undertake the analysis for Europe specifically since it contains some of the only countries worldwide to be already experiencing population decline and since this decline is projected to continue into the future (UN DESA 2013). However, we do not attempt to make any predictions as to whether the findings are applicable globally because population decline is not yet a global phenomenon, and it is still unclear whether the trends seen in Europe will spread worldwide. Nonetheless, it is relevant to study Europe as a possible

example of what may occur in other regions with regard to declining populations. 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. Of course, it must be recognized that, even within Europe, cultural, political, economic, and environmental differences exist between and even within countries that likely have an effect on population and human settlement change.

We first establish how both population and nighttime lights have changed between 1992 and 2012. We then address the relationship between population change and change in nighttime lights and identify whether population decline is reflected in nighttime lights. Finally, we draw from Second Demographic Transition (SDT) theory to examine if the age structure of the population or GDP can better explain the changes in nighttime lights.

European population dynamics

The steep rise in global population during the 20th century has been attributed to a process known as the demographic transition which refers to the shift from high birth and death rates to low birth and death rates that countries undergo as they industrialize (Kirk 1996; Weeks 2008). During this transition, population growth rates first accelerate then begin to slow once again until they stabilize (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 (Lee 2003; Weeks 2008).

In Europe, the demographic transition has not culminated in stability with no population growth, as was initially expected. Fertility levels have continued to drop below replacement level which has led to negative rates of natural increase (Kohler et al. 2002; Lesthaeghe 2010). For the time being, net migration has compensated, and the population of Europe as a whole continues to grow, albeit at a very slow rate. However, net migration cannot indefinitely sustain population growth. In fact, Europe has already seen decline in population in certain countries and regions and will, by approximately 2020, begin to experience decline as a whole continent (UN DESA 2013). Europe has moved toward ground not covered in the original demographic transition theory.

The SDT is a term that is now used by some scholars to describe the persistent declines in fertility as well as accompanying demographic changes. It provides a

characterization of and explanation for what is seen as a new stage in countries' demographic development that brings with it sustained, sub-replacement fertility levels, a diversification in living arrangements, a disconnection between marriage and procreation, and no stationary population (van de Kaa 2002; Lesthaeghe 2010, 2011). 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 (van de Kaa 2002; Lesthaeghe 2010, 2011).

A derivative of the SDT is a changing population age structure. 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). 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.

Population and human settlement patterns

Population is a key driver of land use and land cover change; however, its relative importance among 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).

Urbanization is a key process which has accompanied population growth. It is commonly linked to economic development which has been shown to drive population growth. 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. Following this early rise, the pace of urban growth gradually slowed until it stagnated and, in some cases, even declined (Davis 1965). This trend mimics the population change curve of the demographic transition, and it is clear that they are related. While population change may not have led to urbanization, 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 developed area have, for the most part, still increased. This is due to the increase in non-urban development, a second important land development process.

Apart from urbanization, European societies have also moved through stages of suburbanization, desurbanization,

and reurbanization, as described by van den Berg et al.'s (1982) theory of cyclical urban growth and decline. During suburbanization, improvements in transportation and affluence allowed residential development to expand outside of the central city. Meanwhile, core employment continued to thrive, and the suburbs and the central city were integrated functionally. Increased congestion and dissatisfaction with urban life then began to build and led to desurbanization 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.

Parallels can be seen between Davis' (1965) and van den Berg et al.'s (1982) theories of urbanization in Europe and demographic transition theory. Both population and urban development appear to have transitioned in a similar manner 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 an 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?

MATERIALS AND METHODS

A time series exploration of the intersection between population change and change in nighttime lights in Europe was undertaken through country-level change and regression analysis.

Description of data

DMSP-OLS nighttime lights

The annual stable lights composite (version 4) of the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) released by the National Oceanic and Atmospheric Association's National Geophysical Data Center (NOAA-NGDC) was used (NOAA-NGDC 2014a). The DMSP-OLS is a satellite designed to collect global cloud imagery (Elvidge et al. 2004, 2009; Baugh et al. 2010). At night, the visible band is intensified using a photomultiplier tube (PMT), which allows the

sensors to detect clouds illuminated by moonlight (Elvidge et al. 2004, 2009; Baugh et al. 2010). The PMT boosts the detection of light from human settlements, gas-flares, fires, fishing boats, and the aurora (Elvidge et al. 2004, 2009; Baugh et al. 2010).

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. 2009). Currently, there have been a total of six satellites in orbit: F10, F12, F14, F15, F16, and F18. The NOAA-NGDC produces three annual nighttime lights products based on the data collected which are freely available to the public: cloud-free, average visible lights, and stable lights composites. Composites are labeled based on the satellite used to gather the data and the year in which they were gathered. For example, F101992 describes the composite which was generated in 1992 using data collected by the satellite F10.

The stable lights composite 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); however, they are not exactly proportional to the physical amount of light emitted (Henderson et al. 2012). The stable lights composite is filtered to remove ephemeral lights and background noise (Elvidge et al. 2013). Baugh et al. (2010) provide an in depth explanation of the processing required to generate the stable lights composite.

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 centers becomes limited (Elvidge et al. 2004; Doll 2010b; Baugh et al. 2010). This limits analysis using the DMSP-OLS dataset to a coarser scale, for example, the country level, as was selected in this study. It might be interesting to examine the effect of population decline on urban areas; however, such within-city analysis is restricted with the DMSP-OLS data. Furthermore, the dataset overestimates the actual size of lighting on the ground, a phenomenon referred to as blooming. Elvidge et al. (2004) 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. 2004).

While the importance of these issues should not be discounted when dealing with nighttime light data, their effect on the present research is mitigated by the fact that the dataset has global coverage. Thus, there is no change in the quality of the data based on spatial location. That is to say, under similar circumstances, blooming and saturation occur consistently across the globe, regardless of location. This consistency in errors is not the case with other data that are used in social science research. For example, accuracy, reliability, access, and availability of census and survey data differ widely depending on the source of the data and therefore also on the spatial location. Elvidge et al. (2002) explain that “nocturnal lighting could be regarded as one of the defining features of concentrated human activity” and therefore, that nighttime light data provide one of the best sources for depicting urban land use expansion and change both at continental and global scales.

While saturation and blooming do not present a significant hindrance to the current study, a third known issue with the DMSP-OLS data, mainly that the sensor has no on-board calibration, does introduce problems for the time series analysis to be undertaken and has therefore been taken into account in this study. Each OLS has different detection limits and saturation radiances and degrades at a different rate through time. Additionally, 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. This means that there is no consistent point from which to compare lighting intensity across multiple years, which limits the applicability of the dataset for cross-year analysis. However, Elvidge et al. (2009, 2013) recognized this problem and developed a regression-based intercalibration technique to calibrate composites against a base composite and allow for improved cross-year analysis. This technique was used in this study to improve the suitability of the dataset for time series analysis and will be subsequently explained.

Nighttime light data preparation

Each DMSP-OLS sensor has a different “base point” from which all data are gathered and this point changes over time as the sensor ages and deteriorates. The base point is also never recorded by the instrument, so it is impossible to know how the values collected by each sensor on each pass relate to each other. For this reason, calibration between the composites is required in order to attempt to bring them all to the same “base point” so that their values can be more accurately compared. As stated earlier, Elvidge et al.’s (2009, 2013) regression-based intercalibration technique was used in this analysis. The technique selects one base composite, that with the highest sum of DN values, and adjusts all of the other composites to match its data range.

After selecting the base composite, samples of lighting from selected urban regions are extracted to be used as candidate calibration areas. For each candidate area, a comparison between the DN values of the base composite and each other satellite year is conducted using scattergrams. The aim is to find a candidate region where lighting did not change much over time and where the full range of DN values is represented. Elvidge et al. (2009, 2013) determined that this is evidenced by a strong diagonal axis, minimal width along the primary axis and few outliers in the scattergrams. The optimal candidate region is then used to develop a second-order regression model for each satellite year. The model is of the following form:

$$y = C_0 + C_1x + C_2x^2,$$

where x is the DN value for the base year, y is the DN value for the calibration year, and C_0 , C_1 , and C_2 are the regression coefficients.

In this study, F182010 was chosen as the base composite. Nomenclature of Territorial Units for Statistics level II regions (NUTS II) were chosen as the candidate calibration regions, and a sample of NUTS II regions with major urban areas was selected. NUTS classification is a standard developed by the European Union to subdivide countries for statistical purposes. Level II is the second subdivision and in most countries corresponds to regions which subdivide states or provinces. It was deemed that regions of this size provided enough individual coverage of major urban areas while keeping the number of regions to be examined manageable. Following the examination of the selected candidate regions using scattergrams, it was deemed that Sicily provided the best fit to the criteria, consistent with the findings of Elvidge et al. (2009, 2013). The second-order regression model was then developed, and the resulting calibration coefficients (C_0 , C_1 , and C_2) are shown in Table 1. These coefficients were applied to each composite using the above stated regression model so that a new value (y) was calculated based on the original value (x) for each pixel. Any values over 63 were truncated so that the range of the values remained between 0 and 63.

Following intercalibration, the composites from the same year but different satellites were averaged into one composite. 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 1 year of nighttime lights between 1992 and 2012. The composites were then reprojected into a Lambert Azimuthal Equal Area projection, using a nearest neighbor resampling technique and a cell size of 1 km².

Finland, Norway, Sweden, Iceland, and Russia were excluded from the analysis because of decreased accuracy of the nighttime light data. At the extreme north latitudes of

these countries, fewer cloud-free observations are included 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 et al. 2012).

In order to be comparable with the country level population, GDP, and other demographic data, the night-time light data were aggregated to the country level. The total lighted area for each country was used as the aggregate measure of lighting.

Demographic data

Population data as well as data regarding the percentage of the population between 0 and 14 and over 64 years of age

Table 1 Calibration coefficients for cross-year analysis of stable lights composites, derived from intercalibration regression model

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
F15	2003	−0.0185	1.7744	−0.0133
	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
F16	2005	−0.0311	1.7861	−0.0130
	2006	−0.0035	1.8146	−0.0135
	2007	0.1053	1.8927	−0.0151
	2004	0.0017	1.6334	−0.0107
	2005	−0.0734	1.8601	−0.0143
	2006	−0.0087	1.5660	−0.0091
F18	2007	−0.0205	1.3583	−0.0060
	2008	−0.0179	1.4378	−0.0073
	2009	0.1349	1.5622	−0.0095
	2010	0.0000	1.0000	0.0000
	2011	0.0938	1.2698	−0.0055
	2012	0.0122	1.1210	−0.0024

were downloaded from the World Bank World Development Indicators open data database for each country on a yearly basis from 1992 to 2012 (The World Bank Group 2014). Age-specific population data were not available for Liechtenstein.

Gross Domestic Product (GDP) data

Official GDP data were also obtained from the World Bank World Development Indicators open data database for each country on a yearly basis from 1992 to 2012 (The World Bank Group 2014). For five countries (Croatia, Estonia, Ireland, Liechtenstein, and Montenegro), only partial data were available. All GDP data are expressed in constant 2005 US dollars (USD). The figures are converted from local currencies using 2000 official exchange rates.

Methodology

Initially, the overall change in population and lighted area between 1992 and 2012 was calculated. A quadrant graph of the change was generated, where the horizontal axis represented the absolute change in population from 1992 to 2012, and the vertical axis represented the change in lighted area. The change in lighted area was further explored through a composite map of three time periods (1992, 2002, and 2012) in the Red–Green–Blue (RGB) scale. 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 color combinations, in which each represents a different type of change, as summarized in Table 2.

However, measuring change from 1992 to 2012 can hide fluctuations within the 21 year period, most relevantly in countries where a shift occurred sometime during this period. Therefore, typologies were created to group countries according to the specific trends observed.

Table 2 RGB composite color interpretation

Pattern	Interpretation	Color
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

To examine the relationship between population change and lighted area change more closely, each country's data were divided into periods of population increase and population decrease using the typologies. Countries with erratic populations were ignored. Those countries with steadily increasing or decreasing populations were not subdivided. The linear correlation between population and lighted area was then calculated for each country separately for periods of population growth and decline.

Finally, bivariate correlations between each of (a) the percentage of the population younger than 15 years of age (U15), (b) the percentage of the population older than 64 years of age (O64), and (c) the GDP and lighted area were calculated for each country during periods of population increase and decrease separately. These relationships were graphically compared to the relationship between lighted area and population.

RESULTS

Within the study area, the total population increased by approximately 4 % between 1992 and 2012. Despite this fact, several countries experienced an overall decline in population. The total lighted area increased by approximately 42 % between 1992 and 2012. Figure 1 maps the percent change in population and lighting between 1992 and 2012. Regional divisions can clearly be seen in terms of population. While Western Europe generally experienced growing populations, the East experienced consistent decline. In the case of lighting change, a regional division is not as apparent. However, the three countries that experienced consistent decline (Slovakia, Moldova, and Ukraine) are exclusively located in Eastern Europe.

Figure 2 shows the population change relative to the change in lighted area. Population decreased while lighting increased (Q1) in 31 % of countries and all were in Eastern Europe. Population and lighting increased together (Q2) in 57 % of countries. These countries were for the most part in Western Europe, with the exception of Czech Republic, Poland, Montenegro, Slovenia, and Macedonia. There is only one country (Slovakia) where population increased while lighting decreased (Q3). Finally, two countries, Ukraine and Moldova, both in Eastern Europe, saw both population and lighting decrease (Q4).

Figure 3 maps the spatial distribution of these changes. Here the spatial divisions can be seen most clearly. Population decreased in Eastern Europe (Q1, Q4); however, lighted area only followed in two countries (Q4). Other countries with decreasing lighted area are spread throughout Europe, with no clear spatial pattern; however, these do not have decreasing populations (Q3). The most common trends are population and lighted area growing

% change 1992 to 2012		
Standard deviations	Population (a)	Lighted area (b)
< -1,5	-22.5% to -16.2%	
-1,5 to -0,50	-16.1% to -3.4%	-17.0% to 23.8%
-0,50 to 0,50	-3.3% to 9.4%	23.9% to 212.1%
0,50 to 1,5	9.5% to 22.2%	212.2% to 400.4%
1,5 to 2,5	22.3% to 35.0%	400.4% to 820.0%
> 2,5	35.1% to 35.5%	

Fig. 1 Change in population and lighted area between 1992 and 2012. **a** Change in population (standard deviations from the mean). **b** Change in lighted area (standard deviations from the mean)

together (Q2), as seen in Western Europe, or lighted area growing and population declining (Q1), as in Eastern Europe. It is clear, therefore, that in general, lighted area

Fig. 2 Change in population vs. change in lighted area, 1992–2012. **a** Change in lighted area in all study countries. **b** Larger scale view of change in lighted area for greater detail. Poland, Romania, Ukraine, Italy, France, Spain and United Kingdom removed

Fig. 3 Change in population vs. change in lighted area, 1992–2012. A spatial illustration of change quadrants from Fig. 2

and population are not tied together over time. Lighted area has, for the most part, followed an increasing trajectory throughout Europe, regardless of the direction of population change.

Figure 4 presents the change in lighted area from 1992 to 2002 and further to 2012. Using Table 2 as guidance to interpret the maps, it is clear that overall lighting decline can be seen in Moldova, Slovakia, and Ukraine. Additionally, there is instability in parts of Spain, France, Germany, Hungary, 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.

Table 3 is a more specific examination of the population and lighting trajectories for each country. The typologies divide Europe into groups based on the type of population change experienced by each country over the 21 year study period. The East–West division in population change can still be seen. Western European countries tend to have experienced more steadily increasing populations, while Eastern European countries have experienced more fluctuation in their population trajectory. Again, there is no clear regional division in lighted area change.

Table 4 presents the correlations between population and lighted area for periods of population increase and decrease separately. Only in 23 % of significant cases are population and lighted area coupled in decreasing populations, while they are coupled in 93 % 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, which 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.

Figure 5 shows the comparison between the correlations for lighted area and each of O64, U15, and GDP against the correlation between the lighted area and population. Evaluating the graphs along the y-axis, observations in the upper half show periods where the variables and the lighted area were coupled and in the bottom half where they were uncoupled. Looking at the x-axis, those observations to the right of the vertical axis show that the population and lighting indicator were coupled, while to the left, they were not. The interpretation of these graphs is therefore that if a variable is 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.

Regardless of whether populations are increasing or decreasing, the lighted area and O64 have a tendency to have a positive correlation. 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. In terms of periods of population increase, Ireland and Czech Republic are outliers.

The results with regard to U15 are similar to those of O64. Regardless of whether populations are increasing or decreasing, the lighted area and U15 have a tendency to

Fig. 4 Pixel level lighted area change, 1992, 2002, 2012. **a** RGB composite for all eight types of change. **b** Composite grouped by major change pattern

have a consistent correlation; however, in this case, it is a negative correlation. This shows that U15, like O64, serves as an explanatory factor for lighting change. Regardless of the population trajectory, the lighted area moves in the opposite direction of U15.

The trends in the correlation between GDP and lighted area are similar to those between O64 and U15 and the lighted area. Regardless of whether populations are increasing or decreasing, the lighted area and GDP tend to have a positive correlation. In general, GDP does not explain more of the variation in lighted area than do O64 or U15.

DISCUSSION

The examination of population change 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 %). In Western Europe, the major trend has been toward steady population growth; however, in Germany, Greece, and Portugal, population

decline set in after 2000. It remains to be seen whether these reversals will continue or whether they are temporary fluctuations in the population trajectories. 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 2013). 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. Only three countries, Slovakia, Moldova, and Ukraine experienced overall declines in lighted area. While these three countries are all located in Eastern Europe, it cannot be concluded that Eastern Europe is experiencing lighted area decline since there are many other Eastern European countries that experienced lighted area growth; however, it could be said that lighting decline is more likely to occur in Eastern Europe than 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

Table 3 Summary of population and lighted area change trajectories by type of change over time

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

Eastern and Western Europe than it would be in the spatial distribution of the results.

A strong relationship between lighting and population on a yearly basis has been identified in previous studies (Elvidge et al. 1997; Sutton et al. 2001; Pozzi et al. 2002); however, this relationship does not hold when examined over time for each country separately. 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 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 lighted area decline (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.

Table 4 Correlation population vs. lighted area by period of population increase and decrease

Country	Lighted area	
	Pearson's <i>R</i>	<i>R</i> ²
<i>Periods of population decrease</i>		
Albania	−0.84***	0.70
Belarus	−0.47**	0.22
Bulgaria	−0.39*	0.15
Czech Republic	−0.60*	0.36
Estonia	−0.76***	0.58
Germany	0.69**	0.48
Greece	0.84	0.70
Hungary	−0.10	0.01
Latvia	−0.75***	0.56
Lithuania	−0.77***	0.59
Macedonia, FYR	−0.93	0.86
Montenegro	−0.92***	0.85
Portugal	0.92	0.84
Republic of Moldova	0.77***	0.59
Romania	−0.51**	0.26
Serbia	−0.31	0.10
Slovenia	−0.82**	0.67
Ukraine	0.49**	0.24
<i>Periods of population increase</i>		
Austria	0.66***	0.43
Belgium	0.23	0.05
Czech Republic	−0.70**	0.50
Denmark	0.52**	0.27
France	0.54**	0.29
Germany	0.93***	0.87
Greece	0.78***	0.60
Ireland	0.66***	0.43
Italy	−0.30	0.09
Liechtenstein	0.80***	0.64
Luxembourg	0.39	0.15
Macedonia, FYR	0.22	0.05
Malta	–	–
Montenegro	−0.08	0.01
Netherlands	0.31	0.10
Portugal	0.89***	0.79
Serbia	0.95*	0.89
Slovenia	−0.41	0.17
Spain	0.49**	0.24
Switzerland	0.65***	0.42
United Kingdom	0.36	0.13

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

The findings on the relationship between the age structure and lighted area and between GDP and lighted area are summarized in Fig. 6. On the one hand, both O64 and GDP

Fig. 5 Correlation comparison GDP, O64, U15 and population vs. nighttime lights

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 positively influences 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

Fig. 6 Summary of correlation comparison findings

under 15 years of age has a negative association with lighting, that is, the fewer young people in a population, the greater the lighted area.

The findings on GDP are consistent with other studies which find that GDP is related to lighting, although most of these studies have not examined the relationship over time (Elvidge et al. 1997; Doll et al. 2006; Ghosh et al. 2010; Chen and Nordhaus 2011). The findings regarding the age structure of the population are new. These reflect how the SDT in general, and not just population, is 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, generally accessing the economy separately and requiring separate housing and infrastructure. 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 (2013) 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, while the growing older population continues to demand expanding 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. Lags of 1 and 5 years were tested, but the lighted area and declining population were still uncoupled. That is, no significant changes in the results were noted. While the current 21-year study period may be too short to test such lags extensively, as new data become available such research may be undertaken. It is possible that population decline will in fact be reflected in nighttime lights with some delay, as it is to be expected that infrastructure development and decommissioning would lag behind population trends. However, the findings of this study suggest that even taking lags into account, population and lighting may continue to be uncoupled and human settlement extent may continue to grow despite declining populations. If lighting is more closely tied to the age

structure of the population and to economic development than it is to population, then population decline may still not be reflected in lighted area, even after some time has passed.

CONCLUSION

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 lighted area. Instead, there is a tendency throughout Europe for 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 lighted area. The relationships between lighted area and 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. 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.

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REFERENCES

- Agnew, J., T.W. Gillespie, J. Gonzalez, and B. Min. 2008. Baghdad nights: evaluating the US military 'surge' using nighttime light signatures. *Environment and Planning A* 40: 2285–2295.
- Baugh, K.E., C.D. Elvidge, T. Ghosh, and D. Ziskin. 2010. Population detection profiles of DMSP-OLS night-time imagery by regions of the world. In *Asia-Pacific Advanced Network, 30th Asia-Pacific Advanced Network Meeting*, Hanoi, Vietnam, 9–13 August 2010. Hanoi: Asia-Pacific Advanced Network.
- Bharti, N., A.J. Tatem, M.J. Ferrari, R.F. Grais, A. Djibo, and B.T. Grenfell. 2011. Explaining seasonal fluctuations of measles in Niger using nighttime lights imagery. *Science* 9: 1424–1427.
- Chen, X., and W.D. Nordhaus. 2011. Using luminosity data as a proxy for economic statistics. *Proceedings of the National Academy of Sciences* 108: 8589–8594.
- Davis, K. 1965. The urbanization of the human population. In *The City Reader*, 5th ed., ed. R.T. LeGates and F. Stout, 20–30. Oxon: Routledge.
- Doll, C.N.H. 2010a. Population detection profiles of DMSP-OLS night-time imagery by regions of the world. In *30th Asia-Pacific Advanced Network Meeting*, Hanoi, Vietnam, 9–13 August 2010. Hanoi: Asia-Pacific Advanced Network.
- Doll, C.N.H., 2010b. Development of a 2009 stable lights product using DMSP-OLS. In *Asia-Pacific Advanced Network, 30th Asia-Pacific Advanced Network Meeting*, Hanoi, Vietnam, 9–13 August 2010. Hanoi: Asia-Pacific Advanced Network.
- Doll, C.N.H., and S. Pachauri. 2010. Estimating rural population without access to electricity in developing countries through night-time light satellite imagery. *Energy Policy* 38: 561–5670.
- Doll, C.N.H., J.-P. Muller, and J.G. Morley. 2006. Mapping regional economic activity from night-time light satellite imagery. *Ecological Economics* 57: 75–92.
- Elvidge, C.D., K.E. Baugh, E.A. Kihn, H.W. Kroehl, E.R. Davis, and C.W. Davis. 1997. Relation between satellite observed visible-near infrared emissions, population, economic activity and electric power consumption. *International Journal of Remote Sensing* 18: 1373–1379.
- Elvidge, C.D., V.R. Hobson, I.L. Nelson, J.M. Safran, B.T. Tuttle, K.E. Baugh, and J.B. Dietz. 2002. Global observation of urban areas based on nocturnal lighting. *LUCC Newsletter* 8: 10–12.
- Elvidge, C.D., J. Safran, I.L. Nelson, B.T. Tuttle, V.R. Hobson, K.E. Baugh, J.B. Dietz, and E.H. Erwin. 2004. Area and positional accuracy of DMSP nighttime lights data. In *Remote Sensing and GIS Accuracy Assessment*, ed. R.S. Lunetta, and J.G. Lyon, 281–292. Boca Raton: CRC Press.
- Elvidge, C.D., B.T. Tuttle, P.S. Sutton, K.E. Baugh, A.T. Howard, C. Milesi, B.L. Bhaduri, and R. Nemani. 2007. Global distribution of density constructed impervious surfaces. *Sensors* 7: 1962–1979.
- Elvidge, C.D., D. Ziskin, K.E. Baugh, B.T. Tuttle, T. Ghosh, D.W. Pack, E.H. Erwin, and M. Zhizhin. 2009. A fifteen year record of global natural gas flaring derived from satellite data. *Energies* 2: 595–622.
- Elvidge, C.D., F.-C. Hsu, K.E. Baugh, and T. Ghosh. 2013. National trends in satellite observed lighting: 1992–2012. In *Global urban monitoring and assessment through Earth observation*, ed. Q. Weng, 97–120. Boca Raton: CRC Press.
- Ghosh, T., R.L. Powell, C.D. Elvidge, K.E. Baugh, P.C. Sutton, and S. Anderson. 2010. Shedding light on the global distribution of economic activity. *The Open Geography Journal* 3: 148–161.
- Henderson, M., E.T. Yeh, P. Gong, C.D. Elvidge, and K.E. Baugh. 2003. Validation of urban boundaries derived from global night-time satellite imagery. *International Journal of Remote Sensing* 24: 595–609.
- Henderson, J.V., A. Storeygard, and D.N. Weil. 2012. Measuring economic growth from outer space. *American Economic Review* 102: 994–1028.
- Imhoff, M.L., W.T. Lawrence, D.C. Stutzer, and C.D. Elvidge. 1997. A technique for using composite DMSP/OLS "city lights" satellite data to map urban area. *Remote Sensing of Environment* 61: 361–370.
- Kirk, D. 1996. Demographic transition theory. *Population Studies* 50: 361–387.
- Kloog, I., A. Haim, R.G. Stevens, M. Barchana, and B.A. Portnov. 2008. Light at night co-distributes with incident breast but not lung cancer in the female population of Israel. *Chronobiology International* 25: 65–81.
- Kohler, H.-P., F.C. Billari, and J.A. Ortega. 2002. The emergence of lowest-low fertility in Europe during the 1990s. *Population and Development Review* 28: 641–680.
- Lee, R. 2003. The demographic transition: Three centuries of fundamental change. *Journal of Economic Perspectives* 17: 167–190.
- Lesthaeghe, R. 2010. The unfolding story of the second demographic transition. *Population and Development Review* 36: 211–251.
- Lesthaeghe, R. 2011. The "second demographic transition": A conceptual map for the understanding of late modern demographic developments in fertility and family formation. *Historical Social Research* 36: 179–218.
- Levin, N., and Y. Duke. 2012. High spatial resolution night-time light images for demographic and socio-economic studies. *Remote Sensing of Environment* 119: 1–10.
- Meyer, W.B., and B.L. Turner II. 1992. Human population: Growth and global land-use/cover change. *Annual Review of Ecology and Systematics* 23: 39–61.

- Moor, A.M., V.A. Alegana, P.W. Gething, A.J. Tatem, and R.W. Snow. 2008. Using remotely sensed night-time light as a proxy for poverty in Africa. *Population Health Metrics* 6: 1–13.
- NOAA-NGDC. 2014a. Version 4 DMSP-OLS nighttime lights time series. Retrieved December 14, 2013, from <http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html>.
- NOAA-NGDC. 2014b. Version 4 DMSP-OLS nighttime lights time series. Retrieved March 17, 2014, from http://ngdc.noaa.gov/eog/gcv4_readme.txt.
- Pozzi, F., C. Small, and G. Yetman. 2002. Modeling the distribution of human population with night-time satellite imagery and gridded population of the world. In *Pecora 15/Land Satellite Information IV/ISPRS Commission I/FIEOS, Pecora 15/Land Satellite Information IV/ISPRS Commission I/FIEOS 2002 Conference*, Denver, CO, 10–15 November 2002. Denver: Pecora 15/Land Satellite Information IV/ISPRS Commission I/FIEOS.
- Small, C., F. Pozzi, and C.D. Elvidge. 2005. Spatial analysis of global urban extent from DMSP-OLS night lights. *Remote Sensing of Environment* 96: 277–291.
- Sutton, P. 1997. Modeling population density with night-time satellite imagery and GIS. *Computers, Environment and Urban Systems* 21: 227–244.
- Sutton, P., D. Roberts, C.D. Elvidge, and H. Melj. 1997. A comparison of nighttime satellite imagery and population density for the continental United States. *Photogrammetric Engineering & Remote Sensing* 63: 1303–1313.
- Sutton, P., D. Roberts, C.D. Elvidge, and K.E. Bauch. 2001. Census from heaven: An estimate of the global human population using night-time satellite imagery. *International Journal of Remote Sensing* 22: 3061–3076.
- The World Bank Group. 2014. World Development Indicators. Retrieved January 30, 2014, from <http://databank.worldbank.org/data/views/variableselection/selectvariables.aspx?source=world-development-indicators>.
- United Nations Department of Economic and Social Affairs, Population Division. 2013. *World population prospects: The 2012 revision, volume II, Demographic profiles* (ST/ESA/SER.A/345). New York: United Nations.
- van de Kaa, D. J. 2002. The idea of a second demographic transition in industrialized countries. In *National Institute of Population and Social Security, 6th Welfare Policy Seminar*. Tokyo, Japan, 29 January 2002.
- van den Berg, L., R. Drewett, L.H. Klaasen, A. Rossi, and C.H.T. Vijverberg. 1982. *Urban Europe, vol. I: A study of growth and decline*. Oxford: Pergamon Press.
- Weeks, J.R. 2008. *Population: An introduction to concepts and issues*, 10th ed. Belmont: Thomson Higher Education.
- Witmer, F.D.W., and J. O'Loughlin. 2011. Detecting the effects of wars in the Caucasus regions of Russia and Georgia using radiometrically normalized DMSP-OLS nighttime lights imagery. *GIScience & Remote Sensing* 48: 478–500.

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