A Thermodynamic Geography: Night-Time Satellite Imagery as a Proxy Measure of Emergy

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Abstract Night-time satellite imagery enables the measurement, visualization, and mapping of energy consumption in an area. In this paper, an index of the “sum of lights” as observed by night-time satellite imagery within national boundaries is compared with the emergy of the nations. Emergy is a measure of the solar energy equivalent used, directly or indirectly, to support the processes that characterize the economic activity in a country. Emergy has renewable and non-renewable components. Our results show that the non-renewable component of national emergy use is positively correlated with night-time satellite imagery. This relationship can be used to produce emergy density maps which enable the incorporation of spatially explicit representations of emergy in geographic information systems. The region of Abruzzo (Italy) is used to demonstrate this relationship as a spatially disaggregate case.

Keywords Emergy · Night-time lights · Geographic information systems · Territorial systems · Thermodynamic geography

INTRODUCTION

Modern human activity lights up the surface of the earth at night. Photographs and satellite images have documented this extensively (Elvidge et al. 2007). The intensity of nocturnal lighting ranges from very high in urban areas to very dim or completely dark in rural and wilderness settings. The spatial distribution and intensity of nocturnal lighting can be mapped globally. These composites of night-time satellite imagery enable the visualization of a geography of human activity (Elvidge et al. 2009a).

These observations of the earth at night result from the direct or indirect consumption of non-renewable energy resources. The use of non-renewable resources characterizes our production processes, transportation, and consumption. Non-renewables are energy and matter forms typified by a marked gap between the rate of resource uptake and the time required by natural cycles to regenerate the resource (Tiezzi 2003). This balance is highly skewed for fossil fuels (Hubbert 1956; Ward et al. 2012). In addition, there is concern that resources historically regarded as renewable (e.g., drinkable water and fertile soil) will be regarded as non-renewable in the coming decades (Vorosmarty et al. 2000; Oki and Kanae 2006; Montanarella and Vargas 2012).

Emergy evaluation (EE) is an environmental accounting method that measures the convergence of different kinds of energy in space and time into a given product or system. Thus, emergy measures the relative contributions of the environment and the economy using a common currency of equivalent solar energy (Odum 1988; Odum and Odum 2000). It is also able to discriminate the use of renewable and non-renewable resources within a system.

In this paper we explore EE with night-time lighting observations to investigate the spatial relationship between the renewable and non-renewable emergy used by national economies and night-time satellite imagery. This study parallels other works that derived a proxy measure of economic activity on the planet from night-time satellite imagery (Sutton and Costanza 2002; Henderson et al. 2009). This research aims to justify the construction of spatially explicit representations of emergy that can be used in a geographic information system (GIS). These representations of emergy will enable analyses within the context of a thermodynamic geography that provides a mechanism for spatializing concrete numeric calculations and

Fig. 1 Defense Meteorological Satellite Program (DMSP) stable lights for the year 2009

measurements of emergy. This will inform our understanding and management of territorial systems (Pulselli 2010).

MATERIALS AND METHODS

Night-Time Satellite Observed Lighting

Nocturnal lighting can be mapped using night-time satellite imagery. This requires a specialized sensor able to detect visible emitted light at night, and a repetition of the observations to filter out areas obscured by clouds (Elvidge et al. 2001). Until recently the only satellite sensor with this capability was the Operational Linescan System (OLS) flown by the U.S. Air Force Defense Meteorological Satellite Program (DMSP). Recently, the VIIRS satellite on the Suomi NPP platform is providing global images of the earth at night with improved spatial resolution (<http://npp.gsfc.nasa.gov/viirs.html>). The DMSP OLS data acquired have been archived since 1992 at the NOAA National Geophysical Data Center (NGDC) (Elvidge et al. 2009b). This data has been used to construct spatial grids of sub-national estimates of population, economic activity, and urban extent (Imhoff et al. 1997; Dobson et al. 2000; Doll 2008; Ghosh et al. 2010a). The area of lighting has been related to population, GDP, electricity consumption, and energy-related carbon emission at national and local levels, and many other applications have been proposed and realized (e.g., Ghosh et al. 2010b; Oda and Maksyutov 2011; Sutton et al. 2012; Froliking et al. 2013). Time series analyses of the DMSP OLS data enable the production of annual cloud-free stable lights images of the average digital brightness value for detected lights. These images have

been filtered to remove ephemeral lights and background noise. In Fig. 1, night-time image data are reported into a global latitude–longitude grid (Plate Carree projection) having a resolution of 30 arc seconds. This grid cell size is approximately 1 km² at the equator. Every pixel in the image is characterized by a digital number value that stretches from 0 to 63. These numeric values of lighting for each pixel found in each territorial context can be extracted, and a “Sum of Lights” (SOL) Index value can be calculated for each nation of the world (Elvidge et al. 2001; Tuttle et al. 2013). SOL is a measure of the total brightness of night-time observed lights within a nation. We characterize the relationship between the SOL of nations and the emergy of nations to determine if night-time lightning is a good proxy to describe and map patterns of resource consumption that are difficult to measure and map.

Emergy Evaluation of a Territorial System

The EE is one of the most used thermodynamics-based approaches to study human activity in territorial systems (Odum et al. 1987; Pulselli et al. 2008a; Brown et al. 2009; Campbell and Ohrt 2009; Pulselli 2010; Campbell and Garmestani 2012). By definition (Odum 1971, 1996), emergy is the quantity of solar energy joules (seJ), directly or indirectly used to obtain a flow or a product.

An emergy assessment accounts for the energy transformations that have historically taken place to produce a product or service. This includes moving back through a hierarchy of transformation processes from a final grade of energy or matter to the primary source of all the process in the biosphere, i.e., solar energy (Odum 1988). The EE helps us to understand the actual environmental cost of the use of resources, measured in terms of the effort of Nature

to provide them for human use, and what kind of mechanisms and biogeochemical drivers are at work for the production of the renewable and non-renewable resources (Odum et al. 1987; Odum 1991; Brown and Ulgiati 1997; Odum and Odum 2000; Pulselli et al. 2011; Coscieme et al. 2013). This suggests that the EE of a territorial system provides a systemic and holistic picture of the territory from a sustainability point of view (Pulselli et al. 2004, 2008b; Bastianoni et al. 2005).

Emergy is calculated using suitable Unit Emergy Values to convert different flows of energy (and matter) into equivalent solar energy. The emergy of a given energy or matter input to a system expresses the equivalent solar energy and/or space and/or time that have been necessary to generate one unit of this input. The total solar emergy of a system is thus a record of all the solar energy used up to obtain all kinds of inputs used by the system. The rules of the Emergy Algebra regulate the EE (Odum 1996). A deeper analysis of this calculation method in the mathematical context of set theory can be found in Bastianoni et al. (2011). The emergy considered as a flow per unit time (measured in seJ year⁻¹) is called empower, and represents the “environmental value” of the resources that the territorial system needs to self-maintain in its present state of organization.

The empower has been calculated for a quasi-global database of countries, described in Sweeney et al. (2007) and Brown et al. (2009). In this database (available from the NEAD¹), renewable and non-renewable inputs, and imported flows of resources, goods and services from outside the national economy are included. The total empower calculated for a national system is composed by different kinds of resources that can be classified: renewable resources (R), like solar energy flow, wind, geothermal heat and rain, are sources of energy and matter that are used slower than they are renewed; local non-renewable resources (N), like soil, water and minerals, are extracted from limited local storages; imported resources (F), like fuels, materials and other goods and services, are limited and must be purchased from outside the system (Morandi et al. 2014). These resources (i.e., local renewable resources and imported and local non-renewable resources) are accounted in an EE and combined into aggregated indicators in order to measure the degree of dependency on non-local resources or the renewable fraction of the total energy use. In general, the empower of a nation depends on the type of land use, processes, technologies, and natural or man-made systems settled within the national boundaries (Pulselli 2010).

¹ The National Environmental Accounting Database, Center for Environmental Policy, University of Florida (<http://www.cep.ees.ufl.edu/need/>).

RESULTS

The Relationship of Non-renewable Resource Use and Nocturnal Lighting

Figure 2a is a scatterplot of the non-renewable fraction of empower and the SOL for more than 100 countries in the years 2000, 2004, and 2008. This represents all the countries for which there is emergy data (NEAD, Sweeney et al. 2007). In Fig. 2b a similar scatterplot is depicted for the renewable fraction of the empower and the SOL.

In Fig. 2, data are expressed on a logarithmic scale. SOL data range from 10³ to 10⁷ and show the highest values for developed countries, and the lowest for sub-Saharan African countries (see Elvidge et al. 2001 for an analysis of the night-time lights of the world). Non-renewable empower values in Fig. 2a range from 10²¹ to 10²⁵ seJ year⁻¹. The value of non-renewable empower takes into account the equivalent solar energy “memorized” in indigenous non-renewable extracted resources (coal, natural gas, oil, minerals, etc.), plus imported goods and electricity, fuels, metals and minerals. Its distribution follows the common definition of developed and developing countries. Non-renewable empower is positively correlated with SOL data for all of the years considered (Fig. 2). This relationship is comparable with the relationship between satellite night-lights data and economic activity and VIIRS data and carbon emissions (Sutton and Costanza 2002; Ghosh et al. 2010a, b). These considerations are coherent with the relationship between emergy and economic activity and with the spatial correlation of emergy and greenhouse gas emission at territorial scale (Bastianoni et al. 2008; Pulselli et al. 2012). The increase of the SOL index value that is related to an increase of the non-renewable empower is similar in all the years considered. However, the slope of the interpolation line has the highest value when calculated for the 2008 dataset and the lowest value when calculated for the year 2000 (the slope is equal to 4E+17 in 2000; 5E+17 in 2004; 6E+17 in 2008). The slope of the relationship between empower and SOL changes with time because, over time, SOL levels off for most nations and empower does not. A given SOL for a nation represents a growing quantity of empower for that nation as time progresses. One explanation for this is the leveling off of SOL over time as a country’s population growth stabilizes and its urban areas densify. For example, changes to the SOL for the United States have leveled off in the last decades because population growth has slowed and urban areas have become more dense (population growth in established cities does not increase light output from those cities proportionally). Nonetheless the empower of the United States has continued to grow.

In Fig. 2b, the renewable empower value ranges from 10²⁰ to 10²⁴ seJ year⁻¹. Its value includes the largest renewable

Fig. 2 Scatterplots of **a** non-renewable and **b** renewable empower (measured in seJ year^{-1}) and sum of lights (measured in digital numbers) for a quasi-global database of countries. Data are reported on a logarithmic scale. Empower data are available for the years 2000, 2004, 2008 from NEAD (<http://www.cep.ees.ufl.edu/need/>—accessed April 2013). **a** Non-renewable empower and SOL are strongly related when calculated for countries. **b** Renewable empower and SOL are not related when calculated for countries

Fig. 3 The sum of lights derived from night-time satellite imagery has been used to estimate the non-renewable fraction of the total emergy used every year in Italy from 1992 to 2009. Calculated values were available for the years 2000, 2004, and 2008 (NEAD, <http://www.cep.ees.ufl.edu/nead/>—accessed April 2013; Sweeney et al. 2007)

source available on land (among sunlight, rain, and wind), the geothermal heat, and the largest available flow from the continental shelf (waves or tidal energy), as recommended by the rules of Emery Algebra (to avoid double counting) (Odum 1996). The distribution of renewable empower data does not follow any classification of development; instead it is related to physical characteristics of different regions of the world (Brandt-Williams and Brown 2010). It is also related to the absolute areal extent of the country considered, while SOL and non-renewable empower seem to be less related with absolute size. A full list of emergy values and related indicators, as well as a deeper analysis and discussion of the national emergy of a quasi-global dataset, are available in Brown et al. (2009).

Night-Time Satellite Imagery as a Proxy Measure of Emergy

A significant positive correlation characterizes the consumption of non-renewable resources and the SOL Index when compared for the world countries (Fig. 2a). The aggregation of night-time imagery at the national scale constitutes a spatially related and replicable method that visualizes and maps the human activity in a country. The strong correlation of SOL and non-renewable empower indicates that night-time imagery provides information about a complex, thermodynamics-based, aggregate measure of human activity. This result allows us to perform estimations and validations of the trend of the non-renewable fraction of empower at national scales, looking backward in time, starting from the year 1992.

This national relationship between SOL and empower is explored using Italy as a test case (Fig. 3). The values of non-

renewable emergy per year are estimated through the conversion of the SOL Index values into equivalent seJ using the regression equation relating SOL to non-renewable empower. The regression equation relative to the SOL and non-renewable empower data for the year 2000 has been used to calculate the empower. The choice is justified by the fact that the SOL and empower data are available for a more numerous dataset of countries for the year 2000 than for other years. A time series of estimates of non-renewable empower for Italy is plotted with three actual values (from the NEAD) represented as squares (Fig. 3) corresponding to 2000, 2004, and 2008. It is notable that the difference between the estimated and the calculated values of non-renewable empower is lower than 5 %.

The trend shows a general increase from 4.5×10^{24} seJ year⁻¹ in 1992 to 5×10^{24} seJ year⁻¹ in 2009. Three steps of faster empower increase can be noted in 1994–1995, 1997–1998, 2002–2003. A stronger oscillation of the data is clear in the section of the trend between the years 2003 and 2009.

Lights and Emergy at the Local Scale: The Case of Abruzzo Region

We tested the DMSP OLS imagery as a proxy of emergy at the subnational scale, taking the Abruzzo region (Italy) as a case study. The Abruzzo region (Fig. 4) is in the central part of the Italian peninsula, covering an area of 10 789 km², with a population of 1 305 500 and a population density of 121 km⁻² (this is lower than the Italian average of 195 km⁻²). The territory extends from the heart of the Apennines to the Adriatic Sea, on a mainly mountainous and wild land. One-third of the region is designated

Fig. 4 **a** 2010 Defense Meteorological Satellite Program (DMSP) and **b** 2012 Visible Infrared Imager Radiometer Suite (VIIRS) image of the Italian peninsula and the Abruzzo region, and scatterplots of non-renewable empower (measured in seJ year^{-1}) and Sum Of Lights (measured in digital numbers) and VIIRS Day/Night Band value (measured in $\text{W cm}^{-2} \text{sr}^{-1}$) for the Abruzzo municipalities. DMSP images saturate increasing the scale and are not clear at local scale. **a** Non-renewable empower and SOL are not related at municipal scale (1 to 10^2 km^2). **b** Non-renewable empower and brightness measurements show a higher correlation at municipal scale when using VIIRS imagery, i.e. increasing the resolution from 1 km^{-2} (DMSP data) to 0.3 km^{-2}

as national or regional parkland. The urbanized area within the region has an easily readable structure, with a dense urban area along the seacoast, spreading around the metropolitan area of Pescara–Chieti, and around the inner towns of L’Aquila, Teramo, and Avezzano. An EE of the Abruzzo region can be found in Pulselli (2010) and Pulselli et al. (2012). In these studies, empower and empower density ($\text{seJ year}^{-1} \text{km}^{-2}$) have been calculated and referred spatially, depicting an emergy-based geography of the studied area. The data gathering followed a bottom-up analysis, thus site specific data have been collected and computed in the EE. The distribution of different emergy flow densities in the whole territory has been performed combining the EE of every one of the 315 municipalities of Abruzzo. These are administrative entities that extend from 2 to 466 km^2 , with 254 municipalities smaller than 50 km^2 , 52 with an area between 50 and 100 km^2 , and 9 bigger than 100 km^2 . In Fig. 4a the relationship between the non-renewable fraction of empower and the SOL Index is reported for the 315 municipal areas of the Abruzzo region.

This case study using DMSP OLS data shows no strong relationship between non-renewable empower and SOL. The failure of this relationship to hold at a finer spatial resolution could occur for several reasons including the following: (1) spatial errors in the imagery or the emergy data, (2) lack of a real relationship at the finer spatial resolution, or (3) a mismatch of the dimensions of the municipalities and the pixels of the satellite observations. In any case, newly available VIIRS night-time satellite imagery allows for further exploration of this relationship at finer spatial resolution. We used newly available higher-resolution imagery acquired in 2012 by the Visible Infrared Imaging Radiometer Suite (VIIRS), on-board NASA’s newest Earth-observing satellite The Suomi National Polar-orbiting Partnership (Suomi NPP). The VIIRS instrument captured its first image on November 2011 and is able to detect brightness values for 0.37 km^2 pixel size at nadir (Steele et al. 2012). In Fig. 4a visual comparison of DMSP and VIIRS imagery of the Italian peninsula and the Abruzzo region shows the increased spatial detail provided by the VIIRS representation of night-time lights relative to the DMSP OLS. Unlike SOL digital number values, VIIRS values are referred to physical units, more specifically $\text{W cm}^{-2} \text{sr}^{-1}$. Figure 4b shows the relationship between the non-renewable fraction of empower and the VIIRS derived brightness values for the 315 municipal areas of the Abruzzo region. The accuracy of using night-time satellite imagery as a proxy measure of non-renewable empower at the municipality level increases with higher-resolution satellite imagery. In Fig. 5b a map of non-renewable empower distribution in the Abruzzo region is presented. Municipalities with high non-renewable empower are indicated with red squares, while municipalities with low

empower are indicated with green squares. A VIIRS derived image of night-time lights in the Abruzzo region may be compared with the non-renewable empower distribution in a GIS (in this case by using ESRI ArcGIS 10.1; Fig. 5).

The territorial system considered is characterized by a particularly strong compartmentalization of urban and industrial areas, which are not widespread as observed in other contexts. This is due to the large portion of the territory occupied by national parks, wilderness areas and natural areas in general, with a very low population density and not very extensive built environment. These park and wilderness areas are predominantly dark in the VIIRS image of the Abruzzo region (Fig. 5a). The effect of this morphology on the distribution of the emergy use was already highlighted by Pulselli (2010), who identified different sections in the Region with a peculiar magnitude of non-renewable empower. In particular, homogeneous zones of high empower, mostly related to housing, mark three main “transects”: one extending all along the coastline, the other two extending toward the interior of the territory, the first one lies along a connection axis between the cities of Teramo and L’Aquila, the second one corresponds to the Pescara–Chieti conurbation, which has a relatively limited westward expansion.

DISCUSSION

A Thermodynamic Geography

Mapping emergy allows the visualization of “an alternative geography based on environmental resource use, in which a territory is interpreted as a continuum of physical and morphological elements, infrastructures and urban settlements, rather than a combination of separated systems” or a “thermodynamic geography” (Pulselli 2010). This is in line with the holistic view of the system that is the basis of the emergy methodology and of the thermodynamic approach. The territory has to be managed as a compromise between energy use and production. This is different from the present management of territories and landscapes in separate compartments, causing isolation and fragmentation. The identification of areas of different levels of use or provision of resources supports decision makers and planners (Burkhard et al. 2012; Syrbe and Walz 2012).

Local renewable sources and the services provided by ecosystems show patterns that can be associated with land-cover maps, following the distribution of environmental assets within the national boundaries; e.g., forests, geothermal heat hotspots, rivers and lakes, fertile soil, sunlight, etc. (Costanza et al. 1997; Sutton and Costanza 2002). This is

Fig. 5 **a** Visible Infrared Imager Radiometer Suite (VIIRS) image of the Abruzzo region; **b** a spatial representation of non-renewable empower; **c** a re-classified VIIRS image is presented together with non-renewable empower

rarely verified for non-renewable sources that are typically imported and are characterized by point source extraction and widespread use. The significant correlation between the total brightness of nocturnal lighting and the non-renewable fraction of empower (Fig. 2a) makes clear the patterns of use of non-renewable forms of energy and matter. The SOL Index can be used as a proxy to map non-renewable empower.

Night-time image data provides a globally available temporal sampling of non-renewable resource use. Compared to energy data, the measures of nocturnal lights show a dynamic that is more in phase with the actual rhythm of our activities. A joint use of these methods will improve the understanding and visualization of the dynamic processes of human-dominated systems such as the industrial, residential, and commercial areas of our cities and towns. Historical series of night-time observation data highlight recognizable dynamics of rapidly evolving territorial systems, e.g., patterns of growth in one or many preferential directions, pulsing dynamics, coordinated transitions, and patterns of diffusion (Frolking et al. 2013). The use of night-time satellite imagery as a proxy of non-renewable empower provides an appealing spatio-temporally explicit vehicle for representing the energy methodology of environmental accounting. Moreover, it enables a verisimilar dynamic estimation of energy aggregates, representative of resource consumption in complex systems, whose detailed calculation is always time and labor consuming, dependent on a large set of statistical data, and basically expert driven, due to the difficulties in applying the method.

Proxy measures nonetheless have their drawbacks. Uncertainties intrinsic in any indirect measure of a phenomenon have to be considered. SOL values are not energy values and it is not possible to disaggregate total brightness values into different forms of non-renewable energy. The SOL Index–non-renewable empower relationship has to be used primarily for mapping and visualization purposes. Applications at subnational scales, particularly in territorial contexts characterized by a large fraction of natural areas, must be used with caution. At this level of detail, the detection and the visualization of non-renewable resource consumption depend on the availability of local data, and on the previous level of knowledge of the spatial distribution of different human activities in a specific region. New higher-resolution night-time imagery, recently acquired by VIIRS, improves these local scale applications. Future research will likely demonstrate that night-time imagery has many useful applications in the area of spatio-temporal representation of energy dynamics.

The Use of Sum of Lights Index for Energy Projections

SOL Index values can be used to mathematically derive non-renewable empower values in time series projections. This application provides an overview of the trend in non-renewable energy use for every nation of the world for a time span wider than most state of the art EEs. These results suggest this application is useful for national scale studies now. Disaggregation of these results to subnational scales requires further study. Nonetheless, the empower values estimated with this technique should be considered as reasonable order-of-magnitude absolute estimates. In addition, these results demonstrate that the night-time imagery provides relative estimates of national energy use that are quite accurate. Empower estimated from SOL data provides information about the trends of non-renewable energy-related indicators. This is especially true when the indicator is calculated as a composition (e.g., a ratio) of data known in a long time series (e.g., the gross domestic product or other highly standardized measures) and the respective non-renewable energy. Empower estimations may also be useful to direct precise data gathering and punctual EEs for a specific period of abrupt change, and to estimate the range of variation between years of maximum and minimum use of non-renewable sources in a country's history. The fact that the newly available VIIRS imagery does not suffer from saturation and can be directly related to actual radiance values suggests that future energy estimates based on VIIRS may be more accurate and useful at finer spatial resolutions.

CONCLUSION

Night-time satellite imagery can be used to provide a spatio-temporally explicit proxy measure of energy to inform a thermodynamic geography. A thermodynamic geography involves the study of the spatial patterns of energy production and consumption. These representations of energy support the joint use of GIS and thermodynamics-based indicators to produce maps (and curve profiles and trends) that show the spatio-temporal patterns of different resource uses within a given territory. It is notable that this depicts a geography that is disconnected from the physical characteristics of different regions of the world. This integration of a thermodynamic indicator of resource consumption with a GIS application enables the visualization of the different resource uptakes at global and regional scales to be included in a multi-layer representation of the dynamics of human activity within a national (or even regional) area. The SOL index of the total brightness of nocturnal lights within a country's territory can be used

to derive non-renewable empower values. This is useful to measure, map, and monitor general trends not currently available in the state of the art energy databases.

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