Using night-time satellite imagery to visualize emergy density in territorial systems

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Abstract

Cities are the emblem of the Anthropocene era we are living in, characterized by a large use of non-renewable resources. The economic activity concentrates in urban systems together with its negative and positive outcomes. More than 80% of global Gross Domestic Product is generated in the cities, where goods and services created by transforming energy and matter inputs are consumed. It is consequently relevant to study the distribution of energy use in urbanized systems. However, data availability and collection can be an obstacle for a dynamic interpretation of non-renewable energy use patterns in an urban rapidly changing environment. Night-lights data collected by satellite imagery can be used as a time-series available and high-resolution proxy for non-renewable energy use in a territory. At the urban scale, the use of this proxy needs to be deeply investigated. In this paper we present a correlation between an index of the "sum of lights" and non-renewable emergy: defined as the amount of solar energy embedded in the non-renewable resources used by a system. This relationship allows to produce density maps of energy consumption which enable the incorporation of spatially explicit representations of urban metabolism in geographic information systems.
Keywords: emergy, night-time lights, thermodynamic geography.

1 Introduction

Cities are human ecosystems and concentrate the positive and negative effects of modern human activities both over the environment and society. Phenomena such as increasing energy and resource consumption, social exclusion, inequality, air and water pollution, but also poverty reduction, production of essential goods and

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services, distributed economic welfare, can be observed and studied within urban environments. The global urban population is growing by 65 million annually, with more than half of world's population now living in towns and cities [1]. Due to the growing importance and complexity of these systems, scientific research is increasingly focused on understanding urban metabolism [2]. In this vein, city is liken to a living organism with emergent properties, more or less resilient, homeostatic, that provides goods and services by using and organizing energy and materials [3].

Patterns and dynamics of energy consumption can be investigated in a time-series by using satellite observed night-time lights emitted by urban and suburban areas [4]. In particular, night-time lights are used as a proxy measure of non-renewable empower: the equivalent solar energy (emergy) embodied in non-renewable resources used by a system in a year. In this paper, the relationship of non-renewable empower with different night-time light products is investigated by focusing on scale-dependency.

2 Methods

2.1 Emergy accounting

Cities process different kinds of energy and materials that need to be accounted together in order to evaluate the overall resource consumption in an urban area. This is possible by converting different inputs in a common unit of measure. Emergy is an environmental accounting tool able to define the equivalent solar energy (seJ) that has been necessary to generate one unit of a resource or energy type [5]. Consequently, the total solar emergy of a system is a record of the solar energy used up, directly or indirectly, to obtain all kinds of inputs used by a system. This is possible by means of conversion factors, called Unit Emergy Values (UEVs) that account for the energy transformations that have taken place to produce a product or service [6]. Thus, the total solar emergy of a system is given by the sum of the energy content of the *i*th input to the system multiplied by the corresponding Unit Emergy Value. The emergy considered as a flow per unit time (measured in seJ $year^{-1}$) is called empower, and it is an expression of the "environmental value" of the resources that the territorial system is using to self-maintain in the present state of organization.

At the national scale, empower data are available for the years 2000, 2004 and 2008 from the National Environmental Accounting Database (NEAD), provided by the Center of Environmental Policy at the University of Florida [7, 8]. Emergy analysis at different territorial scales have been performed for a wide variety of case studies. In particular, the emergy accounting of the Province of Siena (Italy) [9, 10] will be considered in this paper as a case study, in order to test the effectiveness of night-lights based estimations of non-renewable component of empower at the local scale.

2.2 Night-time Satellite Observed Lighting

Cities can be identified and studied from night-time satellite observed images [11]. This provides a systemic picture of the urban system and allows a quantitative estimation of resource consumption at the territorial scale [4]. Until recently, visible emitted night-lights have been exclusively recorded by a specialized satellite sensor, namely, the Operational Linescan System (OLS) flown by the U.S. Air Force Defence Meteorological Satellite Program (DMSP), which data have been archived since 1992 at the NOAA National Geophysical Data Center (NGDC) [12]. The new Visible Infrared Imaging Radiometer Suite (VIIRS), on-board NASA's newest Earth-observing satellite The Suomi National Polar-orbiting Partnership (Suomi NPP), is detecting since November 2011 night-time images with improved spatial resolution and values referred to physical units, i.e. W cm^{-2} sr^{-1} (http://npp.gsfc.nasa.gov/viirs.html). DMSP OLS repeated observations have been filtered to remove areas obscured by clouds, ephemeral lights and background noise. This allowed the production of a series of average annual stable lights images that can be processed in order to extract digital brightness value for detected lights at different spatial scales for different years. DMSP OLS images have been reported into a global latitude-longitude grid (Plate Carree projection), having a 1 Km^2 cell size at the equator. Brightness value in each cell is quantified by a digital number between 0 and 63. These values can be extracted for different territorial contexts and summed in a "Sum of Lights" (SOL) Index value. Thus, SOL is a measure of the total brightness of night-time observed lights within a nation, a region, a province, or a single urban area [13].

A significant positive relationship between SOL and non-renewable emergy has been highlighted for the world nations [4]. This relationship has then been used to estimate time series of non-renewable emergy for Italy, as a case study. However, the same relationship is not maintained at the regional scale, where non-renewable emergy and SOL calculated for different municipalities do not show a common trend. This scale-dependency is probably driven by DMSP OLS resolution, as highlighted when newly available VIIRS night-lights data with increased spatial detail (0.37 Km^2) are explored together with non-renewable emergy at the regional scale, showing again a positive correlation [4].

3 Results and discussion

With an extension of 3821 Km^2, the Province of Siena is the second largest province in Tuscany (Italy). Its territory, divided into 36 municipalities, is characterized by a low population density of 66 Km^{-2}, much lower than the Italian average of 195 km^{-2}. DMSP OLS images for the Province of Siena have been processed and an SOL value extracted for every municipality in a time series from 1992 to 2012 (by using ESRI ArcGIS 10.2). In Figure 1 SOL values are plotted, showing a continuous increase of total emitted light. This trend is synthetically represented in Figure 2, where the 1992 and 2012 DMSP stable lights are compared: darker areas indicate a greater increase in total emitted lights during the time period investigated.

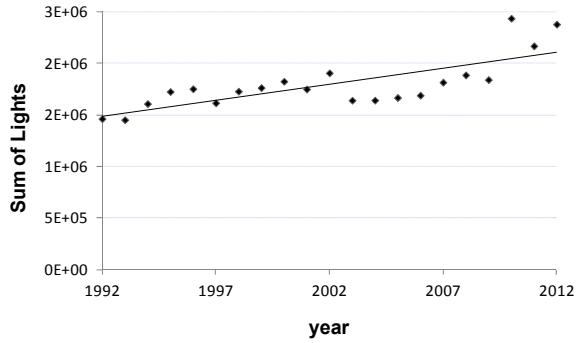

Figure 1: 1992–2012 Sum of Lights (SOL) Index value (measured in digital numbers) for the Province of Siena.

Figure 2 highlights how SOL dynamics in the study area are mostly driven by urban and suburban expansion of the cities of Siena, Poggibonsi and Sinalunga. In particular, a pattern can be noted in Siena municipality night-lights trend, i.e. a major expansion that points directly towards Poggibonsi municipality, possibly leading to a conurbation effect in the very next future (Fig. 2). The data collected, processed, and represented in Figures 1 and 2, can be related with the consumption

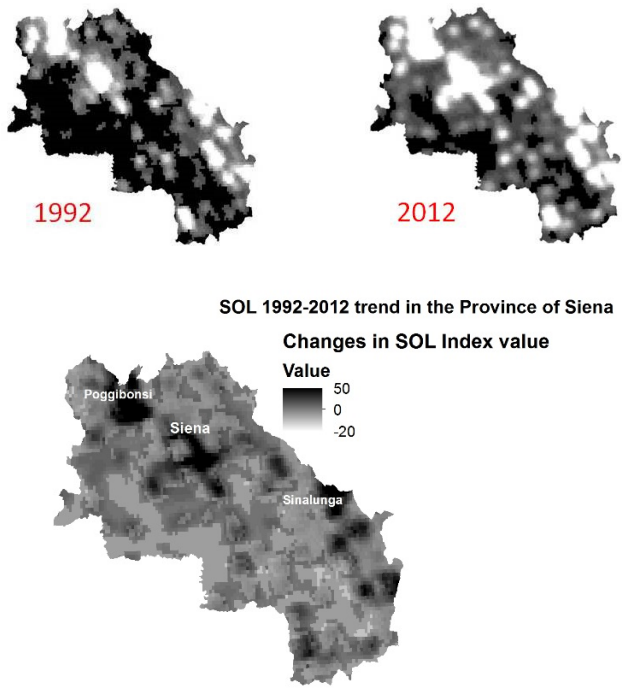

Figure 2: Changes in Defence Meteorological Satellite Program (DMSP) stable lights in the Province of Siena between 1992 and 2012.

of non-renewable resources, as measured by empower, in the 36 municipalities that compose the Province of Siena. These empower data have been calculated by Pulselli *et al*. [9] for the year 2000, while most recent data can be computed from Morandi [10] that performed an emergy accounting for the entire Tuscan region referred to the year 2008.

Coscieme *et al*. [4] highlighted how the relationship between different night-lights products and empower is characterized by scale dependency. In fact, a high correlation of SOL Index and non-renewable empower is observed at the global and national scale, while at the regional scale DMSP images do not relate with empower values. This scale effect can be overcome at the regional scale by using new VIIRS night-light observation data with a spatial resolution equal to 0.37 Km^2 [4]. However, the same relation needs to be investigated at more detailed territorial scales. In Figure 3a the relationship between the non-renewable fraction of empower and the SOL Index is reported with data referred to the year 2000 extracted for every municipality within the Province of Siena. Figure 3b shows the relationship between non-renewable empower and VIIRS data. It is notable how correlation of DMSP SOL Index and non-renewable empower is lost at the very local scale, while using VIIRS observations a positive relationship is maintained also at this scale of analysis. This result is in line with the scale dependency hypothesis, suggesting to only use new VIIRS night-time satellite imagery as a proxy measure for resource consumption at the provincial scale, avoiding the use of DMSP data. VIIRS data, referred to 2012, have been plotted together with 2008 empower data, that represent the most recent available empower data for the 36 municipalities of the Province under study. An updated emergy evaluation of the Province of Siena is needed in order to better investigate the relationship between VIIRS images and non-renewable empower at this territorial scale.

4 Conclusion

Different night-lights products, with different resolution and characteristics, can be used as a proxy measure of non-renewable resources consumed in a territorial system as measured by emergy [4]. This method is, however, dependent on a strong relation between non-renewable empower and a measure of the total brightness of emitted night-lights in the studied area. A significant positive correlation in this sense has been identified by Coscieme *et al*. [4] at the national scale, where night-time satellite imagery can be used to provide a proxy measure of empower in order to "produce maps (and curve profiles and trends) that show the spatio-temporal patterns of different resource uses within a given territory" [4].

In this paper we investigated the scale effect on this methodology, pointing out that different night-lights products are reliable to be used as a proxy for non-renewable resource consumption at different territorial scales. In particular, DMSP imagery, while relevant to be used as a proxy at the national and regional scale, becomes unreliable at the more local scale. However, regardless of the scale, the analysis of night-time observed lights provides useful information to understand the dynamics of urbanization. Historical series of night-time observation data

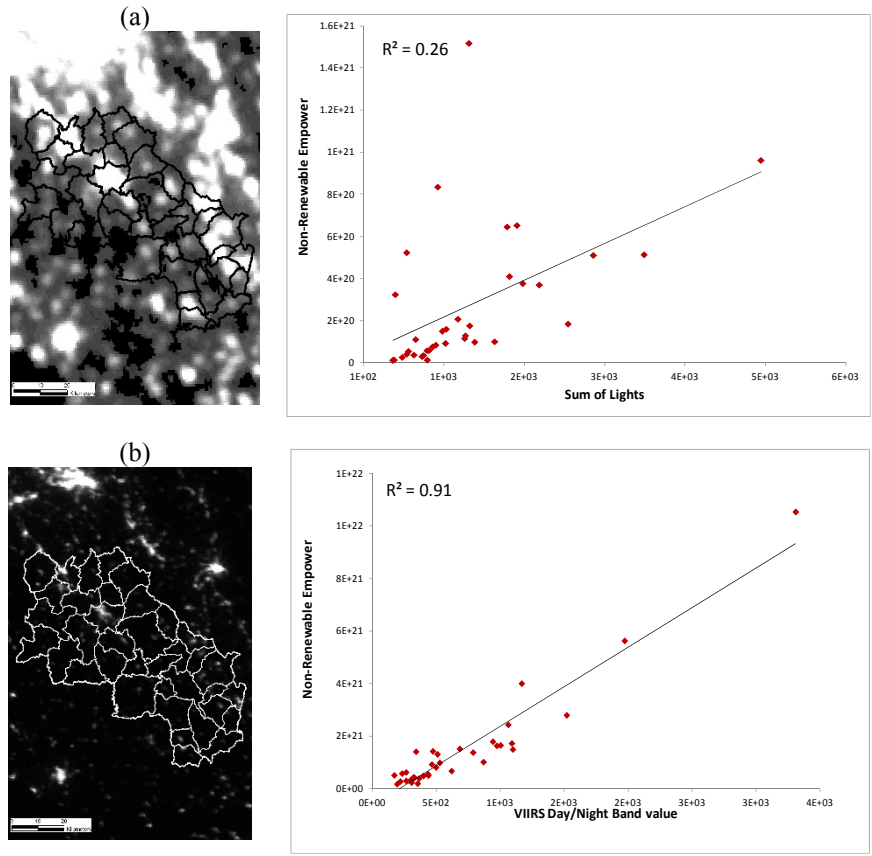

Figure 3: (a) 2000 Defence Meteorological Satellite Program (DMSP) and (b) 2012 Visible Infrared Radiometer Suite (VIIRS) image of the Province of Siena, and scatterplots of non-renewable empower (measured in seJ year^{-1} and available for the year **a** 2000, **b** 2008) and Sum of Lights (measured in digital numbers) and VIIRS Day/Night Band value (measured in W cm^{-2} sr^{-1}) for the municipalities of the Province of Siena. Non-renewable empower and night-lights value show a positive correlation at the local scale exclusively when using VIIRS imagery.

highlight particular patterns of evolving territorial systems, such as patterns of growth in one or many preferential directions, pulsing dynamics, coordinated transitions, and patterns of diffusion [14]. These observations will be crucial to investigate urban metabolic processes and the relationship between an urban system and the natural context that finally provides resources to the city.

References

[1] United Nations, Department of Economic and Social Affairs, Population Division, *World Urbanization Prospects, the 2009 Revision*. New York, 2010.

[2] Kennedy C., Pincetl S. & Bunje P., The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution*, **159**, pp. 1965-1973, 2011.

[3] Pulselli F.M., Coscieme L. & Bastianoni S., Ecosystem services as a counterpart of emergy flows to ecosystems. *Ecological Modelling*, **222**, pp. 2924-2928, 2011.

[4] Coscieme L., Pulselli F.M., Bastianoni S., Elvidge C.D., Anderson S. & Sutton P.C., A Thermodynamic Geography: night-time satellite imagery as a proxy measure of emergy. *AMBIO*, 2013. DOI 10.1007/s13280-013-0468-5.

[5] Odum, H.T., *Environmental Accounting. Emergy and Environmental Decision Making*. John Wiley and Sons. New York, 1996.

[6] Odum H.T., Emergy of Global Processes, Folio #2. *Handbook of Emergy Evaluation.* Center for Environmental Policy, University of Florida, Gainesville, USA, 2000.

[7] Sweeney S., Cohen M.J., King D. & Brown M.T., Creation of a global emergy database for standardized national emergy synthesis. In *Emergy Synthesis 4: Theory and application of emergy methodology* (Brown M. ed.), Gainesville, FL, pp. 23.1-23.15, 2007.

[8] Brown M.T., Cohen M.J. & Sweeney S., Predicting national sustainability: The convergence of energetic, economic and environmental realities. *Ecological Modelling*, **220**, pp. 3424-3438, 2009.

[9] Pulselli R.M., Pulselli F.M. & Rustici M., Emergy accounting of the Province of Siena: Towards a thermodynamic geography for regional studies. *Journal of Environmental Management*, **86**, pp. 342-353, 2008.

[10] Morandi F., A new insight to emergy by means of set theory: theoretical and applicative aspects. Ph.D. Dissertation, University of Siena, 2012.

[11] Elvidge C.D., Sutton P.C., Tuttle B.T., Ghosh T. & Baugh K.E., Global urban mapping based on night-time lights. In *Global mapping of human settlement* (Gamba P., Herold M. eds.), Boca Raton, FL, pp. 129-144, 2009.

[12] Elvidge C.D., Erwin E.H., Baugh K.E., Ziskin D., Tuttle B.T., Ghosh T. & Sutton P.C., Overview of DMSP nigh-time lights and future possibilities. In *2009 Joint urban remote sensing event 1-3*, pp. 1665-1669, 2009.

[13] Elvidge C.D., Imhoff M.L., Baugh K.E., Hobson V.R., Nelson I., Safran J., Dietz J.B. & Tuttle B.T., Night-time lights of the world: 1994-1995. *Photogrammetry & Remote Sensing*, **56**, pp. 81-99, 2001.

[14] Frolking S., Milliman T., Seto K.C. & Friedl M.A., A global fingerprint of macro-scale changes in urban structure from 1999 to 2009. Environmental Research Letters, **8**, pp. 1-10, 2013.