

Statistical modelling and satellite monitoring to evaluate the upward light emissions of public lighting systems

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In this work we propose an approach to estimating the amount of light wasted by being sent towards the upper hemisphere from urban areas. This is a source of light pollution. The approach is based on a predictive model that provides the fraction of light directed skywards in terms of a small set of identified explanatory variables that characterize the urban landscape and its light sources. The model, built via the statistical analysis of a wide sample of basic urban scenarios to compute accurately the amount of light wasted at each of them, establishes an optimal linear regression

function that relates the fraction of wasted flux to relevant variables like the kind of luminaires, the street fill factor, the street width, the building and luminaire heights and the walls and pavement reflectances. We applied this model to evaluate the changes in emissions produced at two urban nuclei in the Deltebre municipality of Catalonia. The results agree reasonably well with those deduced from the radiance measurements made with the VIIRS instrument onboard the Suomi-NPP Earth orbiting satellite.

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1. Background

Well designed lighting systems are key for improving the quality of life in our societies. Besides ensuring appropriate illumination levels to perform the intended visual tasks, a priority in outdoor lighting design is to keep the unwanted emissions of light within reasonable limits. Notwithstanding the recent advances in this field a growing body of research has revealed the accelerated pace at which light pollution is affecting different aspects of our lives. Light pollution -the alteration of the natural levels of nighttime darkness due to artificial lighting- shows an increasing trend and its far-reaching consequences have been reported in such diverse fields as basic science¹⁻³, energy management⁴⁻⁷, ecology⁸⁻¹¹ and human health¹²⁻¹⁶, to mention a few.

In parallel to the study of its consequences considerable effort is being devoted to address this problem from the point of view of its immediate causes, the sources of

light pollution. This complementary standpoint seeks to develop quantitative models for relating with sufficient accuracy and precision the observed light pollution levels to the properties and the spatial distribution of the light sources that produce them^{2,17-23}. Such models are of primary importance for outdoor lighting design, monitoring and management, being instrumental for making informed decisions on public lighting policies. This issue becomes particularly relevant in the present context of massive changes of outdoor lighting systems driven by the worldwide introduction of solid-state lighting (SSL) devices.

One of the main goals in this field is to quantify the amount of wasted light emitted towards the upper hemisphere at neighbourhood, city or metropolitan area levels. Two different and in some sense, opposite, approaches have been usually adopted to address this issue. One of them consists of making educated guesses about the analytical properties of light sources and urban landscapes, establishing from them a theoretically sensible model for the upward radiance of urban areas, and assigning particular values to its numeric parameters in order to adapt the model to the specific circumstances of the site under study¹⁹⁻²⁰.

Detailed studies were performed in Flagstaff, Arizona²⁴. The possibility of obtaining data on lighting installations allowed the research team to predict the total pollutant lumens from a knowledge of the city and to extrapolate to the nearby environment. The radiation emitted upward was given by satellite measurements. Also, the Flagstaff research team worked on improving the study of lighting fixtures^{25,26}. The focus was on determining the amount of pollutant lumens from a range of different sources such as street lighting, sports facilities, business premises etc., and the effect of the upward light output ratio, urbanism and the interference of vegetation on the fraction of luminous flux emitted into the sky.

In the second approach, the overall city radiance can be evaluated by performing a detailed photometric calculation whose inputs are the characteristics of each individual streetlight and the spectral reflectances of the pavements, walls, and buildings²⁷. There is no fundamental reason why this calculation could not be extended to cover a whole urban area but the huge amount of input data and the computing power necessary to carry out the required calculations make this approach unfeasible, except, perhaps, for the simplest situations.

We present in this work a third approach to estimate the amount of urban wasted light. It is based on a multiple linear regression model²⁸ that provides the expected fraction of light emitted towards the upper hemisphere as a function of a relatively small set of identified explanatory variables (significant at a probability of $p < 0.05$) that are directly related to the structure of the urban landscape and to the characteristics of its lighting sources. The relevant variables of the model, as well as the associated regression parameters, are determined via the statistical analysis of the behaviour of a wide sample of basic scenarios, each one depicting a small urban setting (e.g. a street or a segment of a street) with different spatial structure and streetlamp distributions. The upward luminous flux produced by each specific scenario is accurately computed using standard photometric techniques and, provided that the whole sample is able to describe the structure and lighting systems of the town or city under study, a statistical prediction of the overall upward luminous flux for that site can be obtained.

The predictions of the model have been successfully checked against direct observational data acquired from Earth orbit by the VIIRS instrument onboard the NASA Suomi-NPP satellite^{29,30}.

The structure of this paper is as follows: In Section 2 we present the fundamentals, the found relevant variables, the selection procedure, the optimal parameters of the proposed predictive model, and the corresponding model validation. In Section 3 we show how to apply it to a practical situation, by analyzing a case-study corresponding to the overall remodeling of public lighting that took place at two small towns in the Deltebre region of Catalonia. The goal was to determine the overall reduction in skyward emissions produced after that change. The predictions of the model and the results of space-based observations are reported and compared. Section 4 addresses some discussion issues. Section 5 summarizes the conclusions.

2. Statistical approach

2.1. Fundamentals and variables

The proposed approach consists of establishing the statistical correlations existing between the overall luminous flux emitted skywards by an urban area and the main features of its urban structure and lighting sources. The main goal of this work is to build a linear prediction model that provides an estimation of the overall wasted luminous flux in terms of a suitable set of variables.

To achieve that goal we simulated a wide sample (153 simulations) of basic urban scenarios (Figure 1) and computed for each of them the fraction of luminous flux directed towards the sky taking into account the direct emission of the sources as well as the reflections at pavements and building walls³¹⁻³³. The calculations were performed using the software package CALCULUX³⁴ from Philips Lighting. Each of the

scenarios used in this simulation was characterized by different values of the following set of variables:

Luminaire type (t): A qualitative variable describing the type of luminaire, chosen among the most commonly installed ones and defined by their particular photometry. Six main types were considered, labelled from *A* to *F* (see Appendix)

Fill factor (f): The average percentage of the street filled by buildings. For the sake of simplicity, in our numerical calculations this variable was set to take only two possible discrete values: 0 (no buildings), and 1 (fully occupied street with continuous façades on both sides).

Street width (w): Measured in metres

Luminaire height (h): Measured in metres.

Building height (b): The average building height, in metres. Only used when the fill factor is different from zero.

Reflectance of the walls (r): The average reflectance of the walls facing the street when the fill factor is different from zero.

The first two variables are qualitative, and can only take the selected coded numeric values (Table 1). The remaining four variables are quantitative and continuous. The range of values used for each variable was chosen to encompass the typical urban configurations in the region under study. The reflectance of the pavements was set to a fixed value of 0.20. Note that in order to apply this approach in regions with remarkably different urban and/or lighting structures, the ranges of values used to build the predictive model should be modified accordingly, as well as the whole model fitting procedure.

2.2. Model selection

For each simulated scenario we evaluated the total luminous flux produced by the luminaires installed at that site (TIF , Total Installed Flux) and computed accurately the overall luminous flux exiting the place towards the upper hemisphere, directly and by reflection at pavements and walls (UUF , Urbanized Upward Flux). Subsequently, the fraction $F_u = UUF / TIF$ was calculated and finally F_u was expressed in terms of the independent variables $(t, f; w, h, b, r)$ using a multiple linear regression model.

To select the optimal multiple linear regression model, we used an iterative procedure consisting of three steps: 1) An exploratory data analysis, 2) Model Identification, and 3) Model validation. Additionally, the predictive ability of the found model is assessed. Note that the original $n = 153$ set of data was divided into two subsets, one with 90% of the samples and the other with the remaining 10%. The first subset is used for model selection and the later for checking the predictive ability of the fitted model.

An exploratory graphic analysis (matrix scatter plot and boxplots) of the data at hand showed that in order to fulfil the model assumptions a log-transformation should be applied to both, the dependent variable F_u and the quantitative variables w, h, b , and r . Also, this analysis led us to consider interactions between the two categorical t, f variables and some of the quantitative variables.

For model identification, the Best-subsets method is used to help the process of variables selection, and also expert knowledge about the data is taken into account. The found model was statistically validated analyzing residual plots commonly used to confirm that the model assumptions of linearity, constant variance, normality and independence reasonably hold.

To assess the predictive ability of the found model, the 10% of the observations not used to build the model is used. Such predictions are deemed successful if the

actual values of $\text{Ln}(F_u)$ are included within the prediction intervals for a significance level of 0.05.

We remark that the aforementioned iterative procedure is repeated until finding a model with a higher predictive power among all possible candidates. Once the optimal model is found, a cross-validation procedure is entertained.

2.3. Estimated optimal model parameters

The best predictive model for our representative sample of urban scenarios turned out to be:

$$\text{Ln}(F_u) = a_0 + a_1(f) + a_2(t) + a_3(f) \text{Ln}(b+1) + a_4(f) \text{Ln}(r+1) + \dots \\ [a_5 + a_6(f)] \text{Ln}(h) + [a_7 + a_8(f) + a_9(t)] \text{Ln}(w) \quad (1)$$

with the coefficients listed in Table 2. Note that Equation 1 implies that the fraction F_u is given by the product:

$$F_u = K (b+1)^\alpha (r+1)^\beta h^\gamma w^\delta \quad (2)$$

where $K = \exp[a_0 + a_1(f) + a_2(t)]$, $\alpha = a_3(f)$, $\beta = a_4(f)$, $\gamma = a_5 + a_6(f)$, and $\delta = [a_7 + a_8(f) + a_9(t)]$.

The total amount of light emitted skywards (UUF) by an urban area composed of n elementary zones, each one characterized by a particular set of values of the variables of the model, can be easily determined as

$$UUF = \sum_{i=1}^n F_u(i) TIF(i) fd(i) \quad (3)$$

where $TIF(i)$ is the total installed flux at the i -th zone, $fd(i)$ is the corresponding light depreciation factor and $F_u(i)$ is the prediction of the model for that zone, obtained using Equation 2 with the appropriate $(t, f; w, h, b, r)$ values. The sum in Equation 3 is extended to the n zones composing the urbanized area under study.

The found multiple regression model has an adjusted coefficient of determination $R^2_{Adj}=97.1\%$; the higher is the better for the goodness of fit. Also, the model assumptions are reasonably accomplished as shown in the first row of Figure 2. To identify possible influential observations, an analysis of the so-called Cook-distance and leverage measures was performed and none were found influential; see plots in the second row of Figure 2 .

3. Case Study: Results

3.1. Application to the Deltebre area

The current process of massive change of streetlights that is taking place in many places in the world offers exceptional opportunities for carrying out lighting transition studies. It is not uncommon that the light sources of a given town or neighbourhood are almost completely replaced by new models in a relatively short period of time, whereas the emissions from the surrounding areas are kept approximately constant. This makes it possible to perform differential photometry studies in order to assess the influence of these changes on the overall light pollution levels experienced at that site.

One such process took place recently in the Deltebre region, in the province of Tarragona, Catalonia, Spain. Deltebre is a municipality located at the heart of the Ebro river delta natural park, one of the most important wetlands in Europe, home to a rich biodiversity of flora and fauna. The municipality has 12,000 inhabitants distributed in the urban nuclei of Deltebre and Riumar, both surrounded by agricultural fields and relatively isolated from other populated areas. The public lighting system of these nuclei was completely refurbished in 2013, in order to improve lighting efficiency, adjusting and homogenizing illumination levels and reducing light pollution. Before and after the changes were performed we recorded the variables that described the

structure and lighting of a wide set of individual streets in both nuclei, and used them as inputs to our model in Equations 1 - 3 in order to assess the predicted changes in the amount of light emitted towards the sky.

Coincident in time with this process the NASA's Suomi-NPP satellite^{30,31} was taking data of the Earth radiance using the VIIRS (Visible and Infrared Imaging Radiometer Suite) instrument. One of the bands of the VIIRS, the so-called low light imaging or Day-Night Band (DNB), provides nocturnal imagery of the city lights in a wide spectral band ranging from visible to the near infrared (0.5 to 0.9 micrometres). These images, taken at about 01:30 hours mean local solar time from a polar orbit at an altitude of 827 km, 98.7 degree inclination and 102 minutes period, clearly show the upward emissions of the towns in the region under study (Figure 3). The spatial resolution, measured by the cell size, is close to 742 m (Figure 4). The photometric analysis of these calibrated images allowed us to get an estimate of the changes in the flux emitted skywards as observed from space.

3.2. Predicted changes

A total of 695 actual urban scenarios (streets or segments of streets characterized by homogeneous values of the input variables of the model) belonging to the nuclei of Deltebre and Riumar were thoroughly inspected before and after the changes in lighting were performed, and the corresponding values of the $(t,f;w,h,b,r)$ variables were recorded. The predicted fraction of light emitted skywards at each place, F_u , was then obtained using Equation 2 and the overall UUF was calculated using Equation 3.

Taking into account that with the new lighting system there is a 35% luminous flux reduction at curfew time (01:00 hours, UTC+1) so that, from this moment on, the installed flux is set to a value 0.65 of its maximum, the expected magnitudes of the UUF (in kilolumen) before and after the lighting changes are those given in Table 3.

3.3. Satellite radiance evaluation

Figure 5 shows three VIIRS calibrated images of the Deltebre area, two of them taken in April-October 2012 and January 2013 (before the change of the streetlights) and the last one taken in May 2014 (after the change). They are part of larger scale images like the one shown in Figure 3.

The flux emitted skywards from each individual cell was deemed proportional to its radiance, determined by the number of counts. In order to compensate for small time-dependent drifts of the calibration settings we took advantage of the fact that the overall flux of the selected sites located in the region surrounding Deltebre and Riumar (that is, sites #1 to #18 excluding of course the two target places #14-#15, see Figure 3) was estimated to be approximately constant along the period of time considered in this study. Using this constraint we determined the proportionality factors that make it possible to express the data from the 2012 and 2013 images in constant 2014 flux units, enabling that way a direct comparison of the readings. Finally, in order to compare the VIIRS data against the predictions of our model on an homogeneous basis, we evaluated the flux arising from the specific subset of cells within sites #14 and #15 that effectively corresponded to the zones that we had previously catalogued and used to get the estimates of *UUF* reduction shown in Table 3. The small dark signal present in the images (3 counts) was subtracted from all readings previous to this computation.

Figure 6a shows the VIIRS fluxes at the 18 measurement sites for 2012, 2013 and 2014 in constant units. In Figure 6b we plot for each site the ratio of its flux in 2014 (after the changes in lighting at the two target sites were performed) to its mean flux

in 2012 and 2013 (before the changes). Note the pronounced flux reduction experienced at Deltebre and Riumar (sites #14 and #15). The main results are summarized in Table 4.

4. Discussion

Comparison of the results in Tables 3 and 4 shows that it is possible to get a reasonable estimate of the changes of the UUF using a multiple linear regression model that expresses the logarithm of the fraction of light directed skywards from each elementary zone of the town (F_u) in terms of a small set of variables characteristic of the urban landscape.

It is important to stress that the predictive power of this approach is strongly dependent on the correct choice of the sample of basic scenarios used to build the model. In this work we have generated such a sample taking into account the urban and lighting conditions typical of the Catalonian region where this study was carried out (Table 1). Other landscapes, for instance densely built urban districts, could require the generation of a wider sample that capture their main features. Another relevant issue is related to the correct determination of the $fd(i)$ light depreciation factor. This value can be guessed globally or, as it was the case in the present study, estimated by a detailed inspection of the installations in each individual zone of the towns. Typical values for $fd(i)$ are in the range 0.4 to 0.7 for obsolete and old installations, 0.7 to 0.9 for well maintained lighting systems and over 0.9 for newly installed ones. Determination of $fd(i)$ is critical because it is proportional to the totality of pollutant lumens (UUF). Obtaining it may be accomplished through inspections, knowledge of the typology of luminaires and type of city maintenance

(cleaning of luminaires, scheduled replacement lamps ...). For this study the range of fd was narrowed because a complete replacement of the lighting fixtures was performed so $fd(after) = 1$.

In this work we have restricted ourselves to the evaluation of the overall flux directed skywards. The statistical approach described here could also be applied to more detailed photometric information, such as the directionally-resolved urban radiance. In principle, the only requirement is to compute accurately the radiance for each basic scenario and to establish the proper regression model in order to express it in terms of the relevant variables of the environment. The importance of luminous intensity distribution to light pollution is known¹⁹. But the determination from the point of view lighting installations should be complete. As is well known, the impact of light output on light pollution is dependent on where you start from³⁵. Consideration of vegetation cover is therefore important for its masking effect³⁶. Measurements and calculations are performed in this study as if there were a total absence of trees. However, the introduction of this factor should be taken into account in future developments.

The comparison of our predictions with the VIIRS data shall take into account two methodological issues. The first is that the outcomes of the present version of our model are overall fluxes whereas the VIIRS data are radiances. If the radiance distribution of any elementary zone of the town does change after the substitution of the streetlights, the ratio of the radiances after/before measured by VIIRS does not necessarily have to coincide with the corresponding ratio of the overall fluxes. Using a high number of elementary zones (streets or segments of streets) with widely different orientations, as it was our case, helps to alleviate this problem. The second is that our calculations refer to the visible band as defined by the CIE photopic V_λ function,

whereas the VIIRS data correspond to its own 0.5 to 0.9 micrometres band. If the changes of streetlamps are accompanied by noticeably changes in the lamp spectra, the emissions ratios detected by the VIIRS will not necessarily be equal to those determined using the photopic model. In our case-study the new lamps have very approximately the same spectral power distribution as the old ones (excepting for an overall constant factor accounting for their reduced luminous flux), so that it is expected that this issue did not affect the final results significantly.

The outputs of statistical model have been obtained using the lumen, as defined by the CIE photopic curve. You can consider other forms of radiation, such as the CIE scotopic curve. This consideration may be useful in future studies to relate the pollutant emission from distant cities and natural environments sensitive to radiation flux from skyglow.

5. Conclusions

We have developed an approach to predict the fraction of luminous flux emitted towards the upper hemisphere by an urban area, in terms of a small set of variables relatively easy to determine. The relationship between the luminous flux directed skywards and these variables was established using a multivariable linear regression model, based on detailed photometric calculations carried out in a wide sample of basic virtual urban scenarios whose features reflect the prevailing urban landscapes of the region under study. The predictions of the model have been checked against direct on-orbit satellite observations, taking advantage of the massive change of streetlamps carried out at some Catalanian municipalities in recent times.

The statistical model makes it possible to predict the magnitude of a source of pollution: The amount of lumens emitted to the sky, but not quantify its impact: sky brightness or obtrusive light. This way, it can serve as a tool to integrate it into predictive models of impact, minimizing the impact and best practices in lighting design.

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APPENDIX: Types of luminaires included in this study

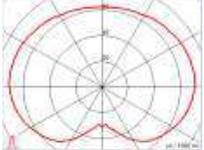
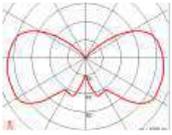
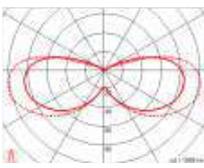
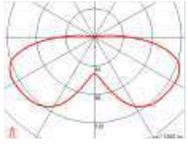
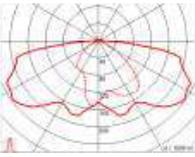
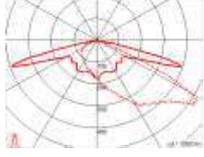
	Description	Image	Typical L.O.R.	Typical U.L.O.R.	Photometry
A	Unshielded globes		80%	50 %	
B	Globes with minimal shielding		60%	40 %	
C	Ornamental lights		60%	35 %	
D	Streetlights without diffuser		70%	10 %	
E	Drop-lens roadlights		70%	5 %	
F	Flat-lens roadlights		80%	1 %	

Figure captions

Figure 1. Computing the upwards emissions in a basic urban scenario.

Figure 2. Validation of the major assumptions of the linear regression model by the residuals analysis.

Figure 3. VIIRS image of the Deltebre region taken in the 0.5-0.9 μm DNB band (2012). The lighting changes analyzed in this work took place in the nuclei of Deltebre (#15) and Riumar (#14).

Figure 4. Close-up view of the main nucleus of Deltebre, with the VIIRS measurement cells superimposed on it. Cell size 742 m.

Figure 5. VIIRS images of the Deltebre area taken (from top to bottom) in three consecutive years.

Figure 6. (a) VIIRS radiance of the 18 selected sites, in constant 2014 units; (b) Ratio of the radiances in 2014 (after lighting changes) to their mean value in 2012-2013 (before changes). Note the pronounced reduction at Deltebre (#15) and Riumar (#14).

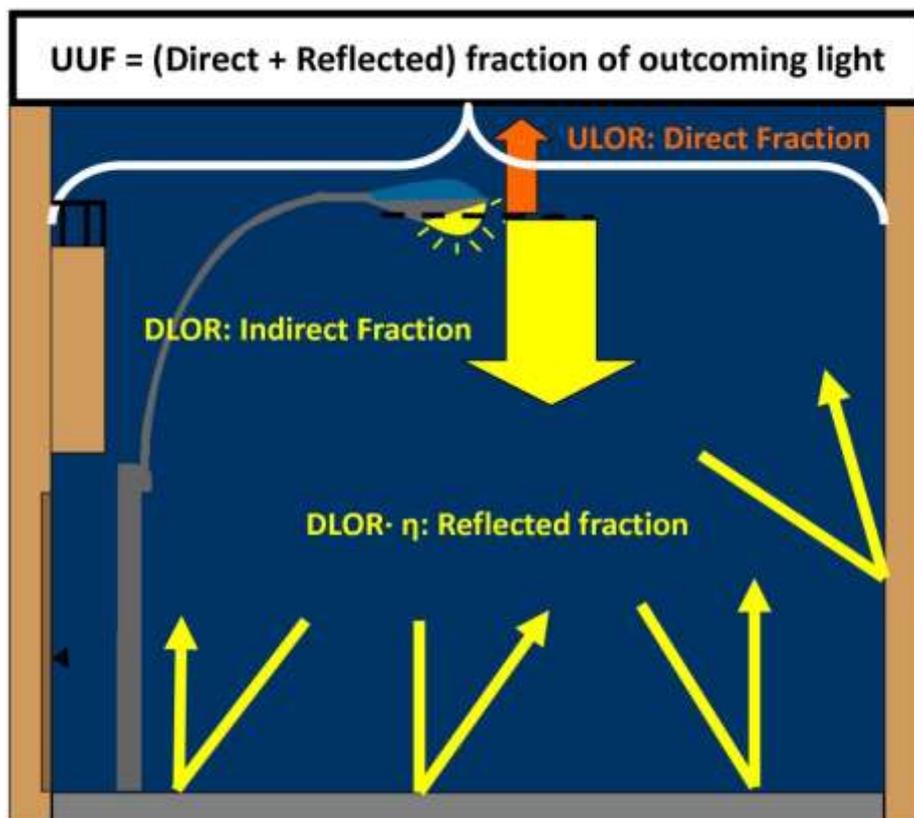


Figure 1. Computing the upwards emissions in a basic urban scenario.

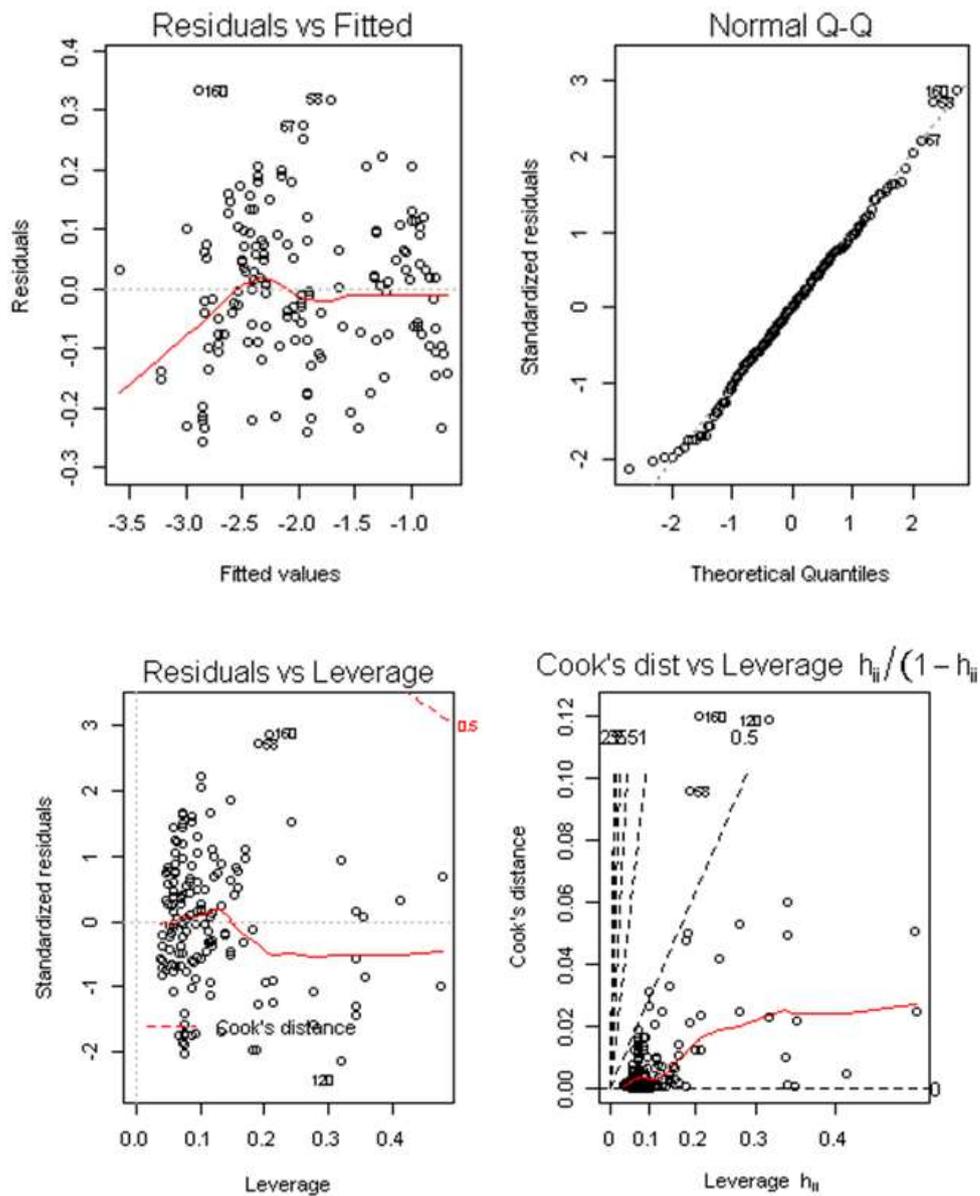


Figure 2. Validation of the major assumptions of the lineal regression model by the residuals analysis.

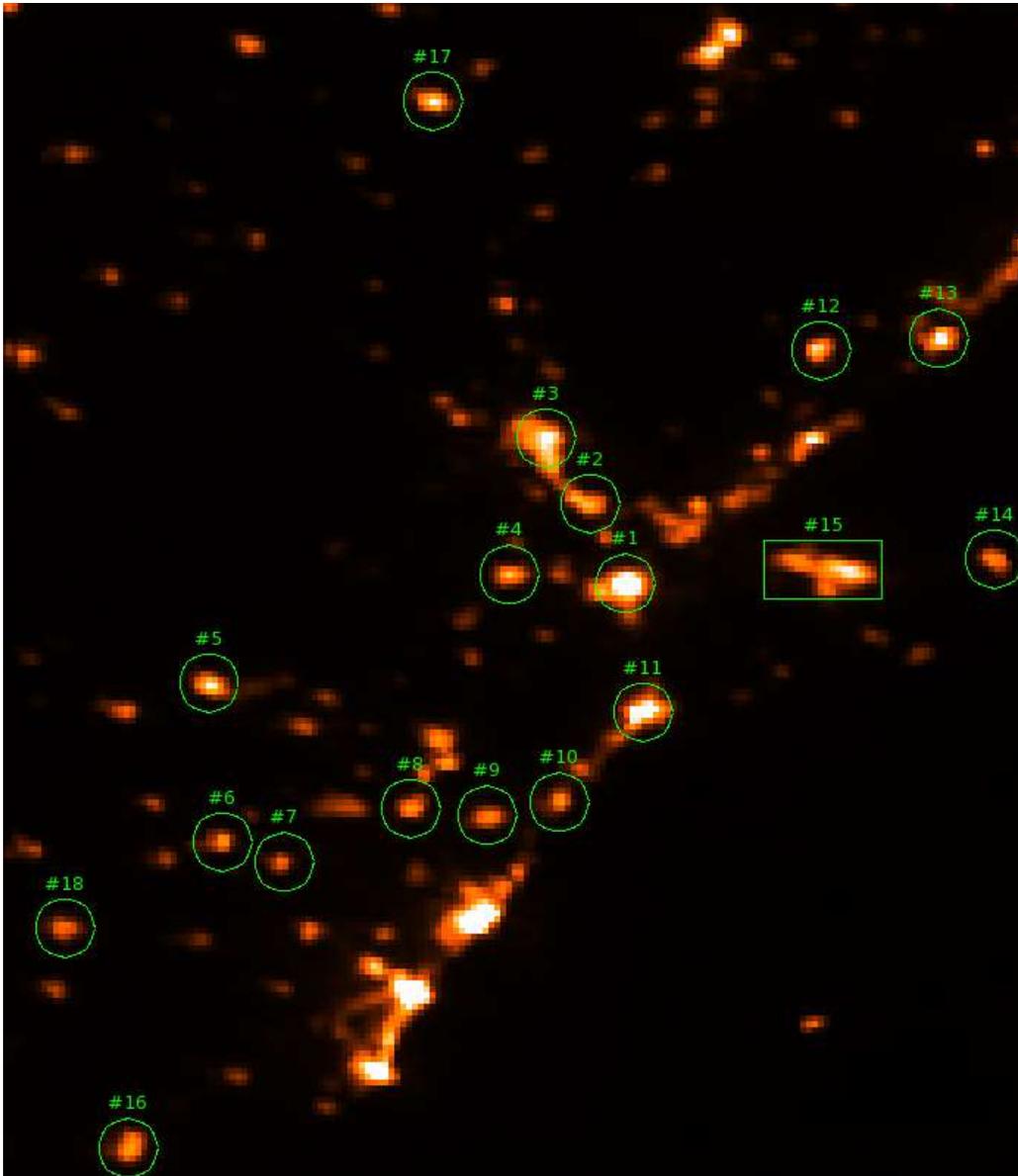


Figure 3. VIIRS image of the Deltebre region taken in the 0.5-0.9 μm DNB band (2012). The lighting changes analyzed in this work took place in the nuclei of Deltebre (#15) and Riumar (#14).



Figure 4. Close-up view of the main nucleus of Deltebre, with the VIIRS measurement cells superimposed on it. Cell size 742 m.

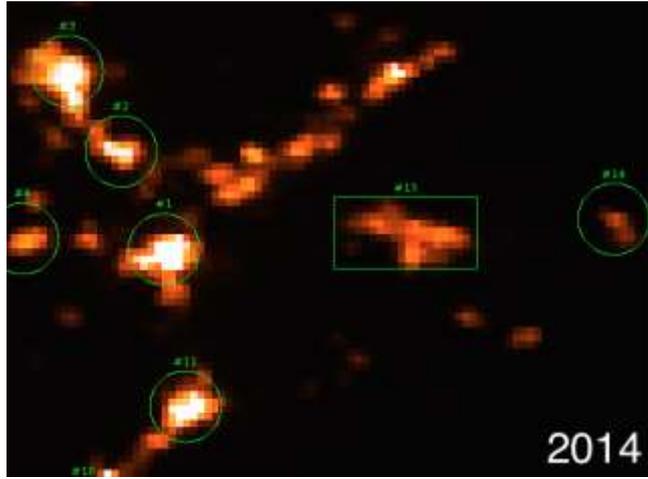
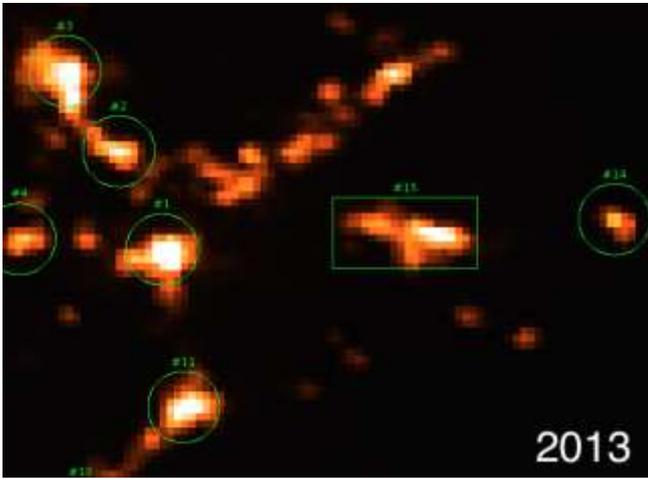
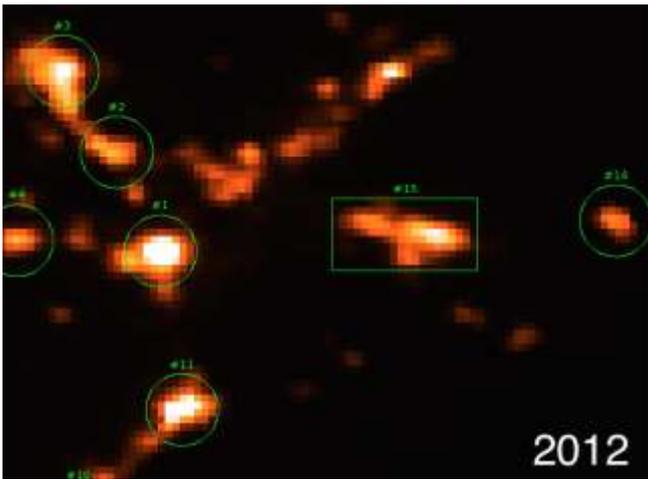
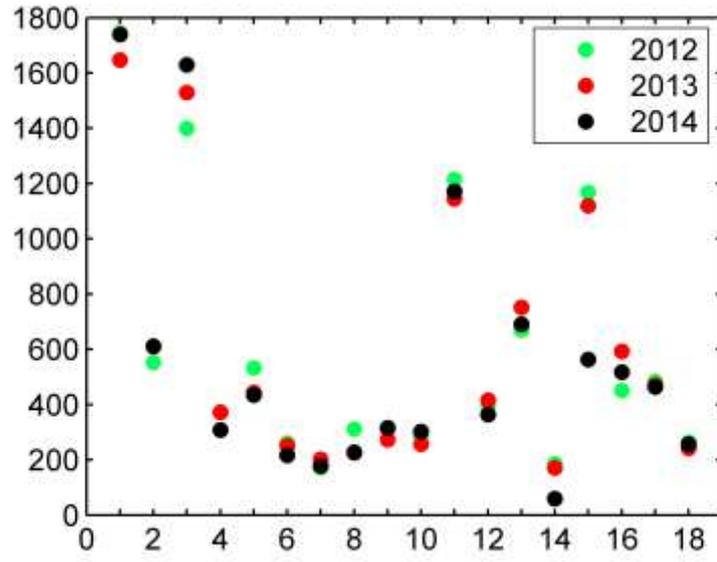
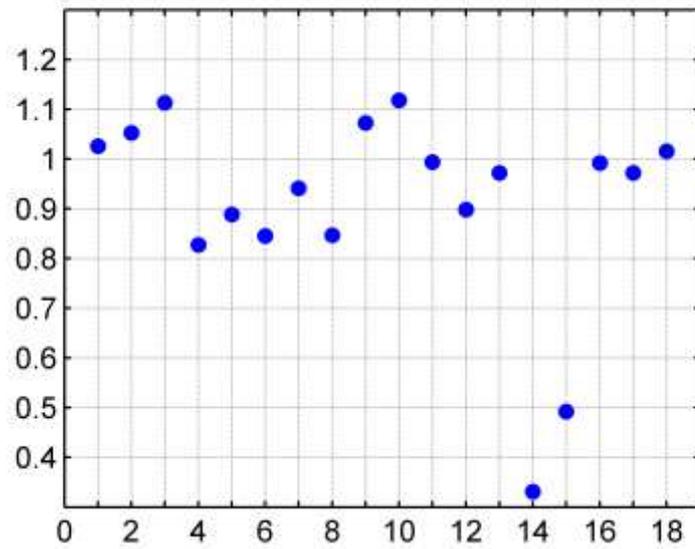


Figure 5. VIIRS images of the Deltebre area taken (from top to bottom) in three consecutive years.



(a)



(b)

Figure 6. (a) VIIRS radiance of the 18 selected sites, in constant 2014 units; (b) Ratio of the radiances in 2014 (after lighting changes) to their mean value in 2012-2013 (before changes). Note the pronounced reduction at Deltebre (#15) and Riumar (#14).

Table 1 Main variables of the model

Variable	Units	Range
Luminaire type (t)	dimensionless	{A, B, C, D, E, F}
Fill factor (f)	dimensionless	{0, 1}
Street width (w)	metres	1 to 40
Luminaire height (h)	metres	3 to 12
Building height (b)	metres	4 to 18
Reflectance of the walls (r)	dimensionless	0 to 0.7

Table 2 Estimated values (standard errors) of the parameters of the model

Constant coefficients

a_0	-0.776 ()
a_5	-0.562 ()
a_7	0.224 ()

Coefficients dependent on f , for $f=1$ *

a_1	-0.522 ()
a_3	-0.676 ()
a_4	1.788 ()
a_6	1.251 ()
a_8	-0.166 ()

Coefficients dependent on $t=\{A,B,C,D,E,F\}$ **

	B	C	D	E	F
a_2	0.073 ()	-1.626 ()	-1.405 ()	-2.514 ()	-1.995 ()
a_9	-0.064 ()	0.682 ()	0.137 ()	0.415 ()	0.221 ()

* Coefficients are equal to 0 in case $f=0$

** Coefficients are equal to 0 in case $t=A$

Table 3 Predicted *UUF* emissions (klm) in the Deltebre area

Site	klm (before)	klm (after)	Ratio	Reduction(%)
Deltebre (#15)	1729.43	751.93	0.435	56.5 %
Riumar (#14)	249.08	81.78	0.328	67.2 %

Table 4 Changes in the VIIRS detected radiance from the Deltebre area

Site	Counts (before)	Counts (after)	Ratio	Reduction(%)
Deltebre (#15)	1143.8	562.8	0.492	50.8 %
Riumar (#14)	178.0	59.0	0.331	66.9%

after: 2014 ; before: average of 2012 and 2013