Understanding and evaluating urban ecological light pollution problems based on Luojia 1-01 nighttime light imagery

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Abstract. Pollution of artificial light at night (ALAN) harms the survival of organisms and destroys the ecological environment. However, there is still a lack of research on understanding and evaluating and identifying ecological risk patterns of urban-scale ALAN pollution. This paper used Luojia 1-01 nighttime light imagery to analyse and evaluate the ecological ALAN pollution. The following conclusions were drawn in the end: 1) the city with the most serious ALAN pollution in the Triangle of Southern Fujian is Xiamen, especially the Huli District and Siming District (Xiamen’s subordinate counties); 2) the ALAN polluted regions in Xiamen Island and Gulangyu Island occupy approximately 3.4 km² (23.4 %).

1. Introduction
With the rapid economic development and urban expansion, the number and scope of artificial light at night (ALAN) have grown rapidly [1]. This represents that the light-dark cycle of the natural nocturnal light environment, on which living things depend, has changed [2, 3]. Unscientific artificial light at night endangers the survival of organisms [4, 5], destroys the ecological environment [6], and causes ecological light pollution [7, 8], which is one of the ecological problems of global concern. The nighttime light imagery from satellites contains information about ALAN, which can help to determine the impact of ALAN pollution [9, 10]. There are biological habitats and breeding grounds in cities, which play an extremely important role in maintaining urban biodiversity. However, there are few studies aimed at understanding, evaluating, and mapping ALAN pollution patterns from the ecological perspective, and quickly analysing and warning of ecological ALAN pollution.

In this paper, we evaluated urban ALAN pollution basing on Luojia 1-01 nighttime light imagery. The study focused on Xiamen Island and Gulangyu Island, with serious ALAN pollution in the Triangle of Southern Fujian, as the main ecological ALAN pollution research areas, and conducted analysis and early warning research on night ecological ALAN pollution.

2. Methods

2.1. Study area
Our study focused on the Triangle of Southern Fujian, including Xiamen, Zhangzhou, and Quanzhou. It is one of the most dynamic economic exploitation zones in eastern China. The intensity and range of ALAN in the Triangle of Southern Fujian are increasing [11, 12], so the habitat and breeding grounds in this area may be affected by ALAN pollution.
2.2. Datasets and Image preprocessing
The nighttime light imagery was acquired by the Luo1-01 satellite (LJ1-01) with a spatial resolution of 130 m. The LJ1-01 imagery was downloaded from the Hubei High Resolution Earth Observation System Data and Application Network [13], accessed on March 31, 2020. The imagery was taken on August 21, 2018. The following equation, provided by Gaofen Hubei Centre, was used to perform radiometric calibration for LJ1-01 imagery.

\[ R = DN \times 10^{-10} \times \frac{10^2}{w} \]  

(1)

where \( R \) is the radiance after absolute radiation correction, in units of W/m²/sr, DN is the grey value of the pixel, and \( w \) is the bandwidth (5.2×10⁻⁷ m). In this paper, the unit of radiance values is nW/cm²/sr.

The ALAN map of the Triangle of Southern Fujian is shown in Figure 1.

![Figure 1. The ALAN map of the Triangle of Southern Fujian.](image)

2.3. Analysis method of ALAN map
To characterize the light intensity of each area, four ALAN pollution indicators were constructed (Table 1), which were extracted using ArcGIS 10.2. We first evaluated and drew the ALAN map of Xiamen, Zhangzhou, and Quanzhou. To understand the status and pattern of the smaller scale, we conducted a further research on the 28 counties and districts under these three cities, including drawing ALAN pollution maps and analysing ALAN indicators.

3. Results

3.1. ALAN pollution in the Triangle of Southern Fujian
Using the LJ1-01 nighttime light imagery, the ALAN pollution map of the three cities was drawn (Fig. 2). It can be clearly seen from the figures that the distribution of night light is centred on artificial light hot spots at night, which diverges to the periphery along the road.
Table 1. ALAN pollution indicators.

| No. | Indicator                              | Interpretation                                                                 | Formula |
|-----|----------------------------------------|--------------------------------------------------------------------------------|---------|
| 1   | Total light intensity ($T_{ALAN}$)     | the sum of the radiance of all pixels in the research region                   | $T_{ALAN} = \sum_{i=1}^{n} X_i$ |
| 2   | Mean light intensity ($M_{ALAN}$)      | the ratio of the sum of the radiances of all pixels in the region to the number of pixels | $M_{ALAN} = \frac{T_{ALAN}}{n}$ |
| 3   | Illumination intensity per unit area ($I_{ALAN}$) | the ratio of the sum of the radiance of all pixels in the area to the area of the region | $I_{ALAN} = \frac{T_{ALAN}}{S}$ |
| 4   | Standard deviation of ALAN intensity ($A_{STD}$) | the standard deviation of all pixels in the region | $A_{STD} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_i - M_{ALAN})^2}$ |

*The unit of $T_{ALAN}$ and $M_{ALAN}$ is nW/cm$^2$/sr; the unit of $I_{ALAN}$ is (nW/cm$^2$/sr)/m$^2$; $n$ is the number of pixels in the ALAN pollution map; $X_i$ is the calibrated radiance value of the i-th pixel in LJ 1-01 ALAN pollution map; $S$ is the area of each region.

Figure 2. The ALAN pollution map of Xiamen, Zhangzhou, and Quanzhou.

The ALAN in Xiamen was brighter and more widely distributed. The digital numbers of the radiance with the lowest value of 89 nW/cm$^2$/sr were assumed to be background noise, while pixels with digital numbers greater than 89 were considered lit areas [14]. The ratios of the area of the lit areas to the area of the city were called the lit area ratio. The area ratio of Quanzhou and Zhangzhou is respectively 1.1% and 0.4%, while that of Xiamen is 8.2%.

In order to quantitatively evaluate the overall ALAN pollution in the three cities, the $T_{ALAN}$, $M_{ALAN}$, $I_{ALAN}$ and $A_{STD}$ of the three cities were compared (Fig. 3). $T_{ALAN}$ shows that Xiamen has the highest total radiance, which is 6.49×10$^6$ nW/cm$^2$/sr, 2.4 and 1.4 times that of Zhangzhou and Quanzhou, respectively. $M_{ALAN}$ and $I_{ALAN}$ show that Xiamen’s average radiance and average intensity are much higher than those of Quanzhou and Zhangzhou, and even nearly 10 times and 20 times higher than the latter two. The result of $A_{STD}$ means that there are some areas with high radiance in Xiamen, which may be due to the light of the non-cut-off luminaires shining up into the sky. According to the survey, these non-cut-off luminaires may be located on top of buildings and roads.
3.2. ALAN pollution in subordinate counties of the Triangle of Southern Fujian

The Triangle of Southern Fujian has 28 subordinate counties. In order to refine the light distribution inside cities, this article explored the ALAN pollution indicators of the 28 counties (Fig. 4). The study selected 17 counties and districts with high light intensity and drew their ALAN pollution maps, respectively (Fig. 5). Jinjiang City, Haicang District, Huli District, and Siming District are the counties with the greatest $T_{\text{ALAN}}$, which contribute the most to urban ALAN pollution in the Triangle of Southern Fujian. The $M_{\text{ALAN}}$ of Haicang District, Huli District and Siming District exceeds 89 nW/cm²/sr. Moreover, $I_{\text{ALAN}}$ and $A_{\text{STD}}$ of these three counties are also the highest among the 28 ones. It is worth noting that these three counties are subordinate counties of Xiamen City.
3.3. Identifying the ecological ALAN pollution pattern in Xiamen Island

Among the 28 counties in the Triangle of Southern Fujian, Siming District and Huli District have the most serious ALAN pollution. Consider that part of Siming District and Huli District is the sea where there is basically no ALAN, this study focused on the two largest islands, namely Xiamen Island and Gulangyu Island. The Xiamen Island is known as the "Sea Garden", and Gulangyu Island is a famous scenic spot, which are like the spring all the year round. There are rich animal and plant resources, advanced economy, and abundant ALAN. The identification of the ecological ALAN pollution pattern is to use the Jenks natural break point method to divide the light pollution area into three levels, namely lightly ALAN pollution, moderately light pollution, and heavily light pollution (Fig. 6).

![Figure 5. The ALAN pollution maps of 17 counties.](image)

![Figure 6. The ecological ALAN pollution map of Xiamen Island and Gulangyu Island.](image)
In these two islands, the area suffering from ALAN pollution is 33.4 km$^2$, accounting for 23.4 % of the total area. The heavily polluted regions covered an area of 3.2 km$^2$ (2.3 %), the moderately polluted regions occupied approximately 8.6 km$^2$ (6.0 %), and the lightly polluted regions covered an area of 21.6 km$^2$ (15.1 %). The ecological ALAN pollution map shows that the lit areas are mainly concentrated in the Yundang Lake area (Fig. 6a) and Wuyuan Bay area (Fig. 6b). In addition, the ALAN pollution is also prominent in the coastal commercial area on the southeast coast of Xiamen Island (Fig. 6c).

### 4. Conclusion

This article proposed a method for understanding and evaluating the problem of urban ecological ALAN pollution: T$_{\text{ALAN}}$, M$_{\text{ALAN}}$, I$_{\text{ALAN}}$, and A$_{\text{STD}}$. By comparing the four ALAN pollution indicators of Xiamen, Zhangzhou, and Quanzhou, it was found that: 1) the average radiance and average light intensity of Xiamen were much higher than those of Zhangzhou and Quanzhou, or even 20 times those of Zhangzhou and 10 times those of Quanzhou; 2) among the 28 counties, the four indicators of Huli District and Siming District far exceed the other 26 counties. Taking Xiamen Island and Gulangyu Island as ecological ALAN pollution research areas, the Jenks natural break point method was used to draw the night ecological ALAN pollution map. The study found that the heavily polluted regions covered an area of 3.2 km$^2$ (2.3 %) and moderately polluted regions occupied 8.6 km$^2$ (6.0 %). The regions suffering from ALAN pollution covered 33.4 km$^2$ (23.4 %).

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