Quantitative Environmental Impact Assessment for Agricultural Products Caused by Exposure of Artificial Light at Night

Yoko Kurahara and Norihiro Itsubo

Abstract Increase in artificial lighting at night adversely affects human activities, wild animals, plants, agricultural crops, and livestock. The Ministry of the Environment defines such adverse effects as “light pollution.” Rice is an agricultural crop subject to the influence of light environment. We used LED lighting rice plants (“Koshihikari” cultivar) grown in a paddy field owned by professional farmers for illumination during the night and evaluated its impact on the rice’s heading and yield by actual measurement. We also factored in the roadway light installed in the paddy field’s vicinity and evaluated its effects on yield. Damage coefficients of light pollution for rice cultivation were developed, 18.9 g/m²/lx (equivalent to 0.046 US\$/m²/lx) for natural white lighting and 16.4 g/m²/lx (equivalent to 0.039 US\$/m²/lx) for light bulb-colored lighting.

1 Introduction

The increased use and scope of night illumination reportedly resulted in an annual 2% expansion of the outdoor area illuminated by artificial lighting around the world over 16 years from 2012 [1].

According to the Ministry of the Environment, the term “light pollution” is defined as an impediment caused by light leakage from outdoor illumination or other forms of lighting and collectively the adverse effects resulting from such an impediment. Reportedly, light pollution affects human activities, wild flora and fauna, and agricultural crops in various ways. Rice is a crop subject to the influence of light pollution [2].

Rice is a short-day crop that promotes flowering beyond a certain critical dark period. Conversion of light receptor phytochrome B (phyB) between Pr-type (red

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light-absorbing type) and Pfr-type (far-red light-absorbing type) is known to be involved in the expression of *heading day 3a (Hd3a)*, a flower induction gene in rice. Normally, plants in places without outdoor illumination absorb red light by photoreaction during day to induce conversion to Pr, thus increasing Pfr amount. Conversely, Pfr decreases at night, promoting *Hd3a* expression. However, it is evident that illumination by outdoor lighting and other light sources during night prevents Pfr from decreasing. Consequently, *Hd3a* expression is suppressed at the transcription level, resulting in delay in or inhibition of heading [3]. For rice of the “Hinohikari” cultivar, illumination above 2 lux (lx) caused a delay in heading; the impact was more prominent when fluorescent mercury lighting, rather than LED lighting, was used, thus suggesting differences in effects depending on the type of light source [4].

Presently, no studies have evaluated the effects of light pollution by the methodology of life cycle assessment (LCA). However, in recent years, the following items have been added as new LCA impact assessment indices: “light pollution,” “ecological light pollution,” and “artificial light emission.” This highlights the importance of evaluating the impact of these new items on the ecosystem and human health [5, 6]. Cucurachi et al. [5] discussed the functional units of light pollution in life cycle impact assessment (LCIA) model. Given the aspects of biodiversity, they reported that not only illuminance (common measurement unit: lx) at a certain place but also light intensity and wavelength are important factors in the functional unit. Therefore, they recommended that joule (J) factoring in electrical power per unit time (watt [W]) be used as the elementary flow and argued that LCIA may be applicable to impact assessment [5].

In Japan, many papers have been published regarding the quantitative assessment results of studies targeting rice. These studies have demonstrated that an increase in the illuminance of night illumination (lx) undoubtedly adversely affects rice yield. Cucurachi et al. [5] reported the possibility of developing a model for further endpoint type damage assessment.

In this study, we evaluated the impact of night LED illumination on the heading and yield of “Koshihikari” rice grown in rice paddies owned by professional farmers. Additionally, factoring in the influence of light leakage from roadway lights installed in the vicinity of the paddy field, we evaluated the effect of light on yield and developed damage coefficients of light pollution for rice cultivation. These findings should serve as a ground for determining how to design and where to install lighting to suppress light pollution.

2 Methods

2.1 Development of a Method for Assessing Light Pollution Impact on Rice Cultivation

2.1.1 Procedures for Assessing the Impact of Light Pollution on Rice Cultivation

Referring to the impact assessment method by Itsubo et al. [7], we developed a calculation flow for light pollution damage factors based on the impact [7]. Coefficients were calculated for each of the following three categories: inventory, impact, and damage analysis. Inventory (*Inv*) was the illumination per unit of area relative to emission from one of the light source units such as outdoor lighting. Influence coefficient (*EF*) was the delay (days) in heading by increased illuminance and the impact on yield caused by the delay. Damage coefficient (*DF*_{light pollution}) was the decrease in yield and loss of profits by increased illuminance. This allows the damage on yield to be quantified when a new light source is added (Fig. 1).

$$\text{Light pollution impact} = \Sigma \text{inventory} (\text{lx} / \text{m}^2) \times \text{damage coefficient} (\text{US\$} / \text{lx or g} / \text{lx}) \quad (1)$$

2.1.2 Effect Analysis

At night, rice of the “Koshihikari” cultivar was illuminated with bulb-colored and natural white LED lights, and their effects on heading and yield were evaluated. Based on the actual measurement data, the correlations between the “illumination and delay in heading” and the “delay in heading and yield of unpolished rice” were quantified to calculate the *EF*. The cultivar used was the “Koshihikari” (*Oryza sativa* L. cv. “Koshihikari”). To explore the impact under a more realistic environment, we conducted the experiment in an approximately 20-a paddy field owned by a professional farmer in Joso, Ibaraki Prefecture, in Japan. On April 30, 2019, rice seedlings were mechanically transplanted at a cultivation density of 18 bundles per m² (one bundle comprising four to six seedlings). For fertilization, only basal fertilizer was applied (nitrogen, 3 kg/10 a; phosphate, 3 kg/10 a; and potassium, 3 kg/10 a). No additional fertilizer was applied, and the rice was cultivated in a conventional manner. Six light units were used (three natural white LED lights and three bulb-colored LED lights, LDR11N-W 9 and LDR11L-W 9, respectively, Ohm Electric, Tokyo, Japan). The illumination period lasted from May 4 after transplantation to September 8, the day of harvest, during which the rice was continuously illuminated during night from sunset to sunrise.

The delayed time of heading was macroscopically determined. The date when all rice plants in the plot had more than 50% of valid stalks bearing ears was regarded

Fig. 1 Damage to rice cultivation due to light pollution

as the date of heading. The rice plants were harvested on September 8 to coincide with the harvesting period of the non-illuminated plot (Fig. 2).

2.1.3 Damage Analysis

Based on the *EF*, a relational expression for illuminance and yield decrease was calculated, which was multiplied by the relative transaction price of rice to calculate the *DF* unit [8].

Fig. 2 Lighting position and irradiation range

2.2 Case Study Using One Unit of Outdoor Lighting

2.2.1 Assessment Method

A case study was conducted using the damage coefficient developed in Sect. 2.1. The impact of light pollution when outdoor lighting was installed in the vicinity of the paddy field was assessed. The light used was one unit of outdoor lighting equipment (e.g., roadway/street lamps). Calculation scenario was set according to the illumination design and placement conditions satisfying the Japan Industrial Standard “JISZ 9111 Road Lighting Standard.” The situation was assumed in which a roadway/street lamp is installed near the paddy field so that crops are most susceptible to light pollution [9]. Some street lamps were inverted cone type, and others were ball-shaped, thus different in shape.

Table 1 Lighting equipment and installation conditions

Inventory data items		Unit	Street light (Inverted cone type)	Street light (ball-shaped)
Lighting equipment	Instrument luminous flux	lm	5955	6625
	Power consumption	W	60	60
	Color temperature	K	5000	5000
	Color rendering index	Ra	70	70
Installation conditions	Light height	m	4.5	4.5
	Mounting angle	°	0	0
	Maintenance rate		0.64	0.64
	Distance from object	m	0	0

2.2.2 Inventory Analysis

The *IF* was the illuminance distribution emitted per one light source unit. The illuminance distribution was calculated using three-dimensional illuminance calculation software “DIALux” [10]. The items necessary for calculating the illuminance distribution were treated as the inventory analysis parameters. Therefore, the adopted parameters were as follows: light source specifications (luminous flux [lm], power consumption [W], and color temperature [K] or color rendering properties [Ra]) and installation conditions (lamp height [m], installation angle [°], maintenance rate, and distance from the object affected by light pollution [m]) (Table 1).

3 Results

3.1 Development of Impact Assessment Methods

3.1.1 Correlation Between Illuminance and Heading Delay

Figure 3 shows the correlation between illuminance and delay in heading. The delay in heading refers to the number of days by which heading was delayed compared with the date of heading in the non-illuminated plot, which was July 26, 2019. As the illuminance increased, the date of heading was delayed. In both natural white illumination and bulb-colored illumination plots, a strong correlation was observed ($r^2 = 0.85, 0.97$). This result was consistent with that reported by Harada et al. [11]. Figure 4 shows the heading delay caused by the experiment. It is affected in a circle along the illuminance distribution. The center of the circle is irradiated with about 300 lx.

Fig. 3 Relationship between illuminance and heading delay days

Fig. 4 Paddy field affected by light on August 26

Fig. 5 Relationship between heading delay days and rice yield

3.1.2 Correlation Between Heading Delay and Yield

Figure 5 shows the correlation between heading delay and yield. The yield of polished brown rice decreased as the delay in heading increased, thus exhibiting a strong correlation ($r^2 = 0.83, 0.87$). In particular, the delay beyond 10–15 days considerably reduced the yield. Compared with the non-illuminated plot ($p = 503$), both illuminated plots (natural white and bulb-colored) exhibited a significant difference at a significance level of 1%.

3.2 Damage Factor Results

3.2.1 Correlation Between Illuminance and Yield

Figure 6 shows the correlation between illuminance and yield decrease. Consequently, the following damage coefficients were obtained: (i) natural white DF , 18.9 g/lx, and (ii) bulb-colored DF , 16.4 g/lx. Decrease in yield was observed from approximately 2 lx with natural white light and approximately 4 lx with bulb-colored light. Given the average yield in Ibaraki Prefecture ($p = 524$), the illuminance that results in zero yield was calculated to be approximately 28 lx with natural white light and approximately 32 lx with bulb-colored. Because this slope has different effects depending on the illuminance, overestimation may occur under approximately 5–15 lx, which is a limitation of this study.

Fig. 6 Relationship between illuminance and yield

3.3 Case Study Results by One Outdoor Lighting Unit

3.3.1 Illumination Distribution in the Paddy Field

The illumination distribution in the paddy field was calculated. The values in the paddy field signified the illuminance per mesh per 1 m² (lx/m²). The maximum illuminance of inverted cone-type street lights exceeded 20 lx and that of the ball-shaped street lights was around 6 lx. The spread of the illuminance greatly varied depending on the shape (Figs. 7, 8).

3.3.2 Endpoint Calculation Results

Figure 9 shows the decrease in the yield (damage amount) per light annually. When installed in the vicinity of the paddy field, the inverted cone-type street lights reduced the yield by 23 kg, whereas the yield reduced by the ball-shaped street lights was 10 kg. Both types of light exhibited light pollution effects. However, the effects varied depending on the distance from and the shape of the light source (due to differences in luminous flux beneath the light source). Therefore, places/situations susceptible to light pollution require countermeasures, such as installation of light shielding plates and changes in illumination position (Fig. 9).

Fig. 7 Illuminance distribution result of street light (inverted cone type)

Fig. 8 Illuminance distribution result of street light (ball-shaped type)

Fig. 9 Result of yield reduction per light/year

4 Conclusion

This study has proposed a framework for light pollution assessment. Additionally, we developed damage coefficients intended for assessing the impact of LED lighting on rice cultivation. Based on these damage coefficients, we conducted a case study of outdoor illumination installed in the vicinity of a paddy field. By actual measurement, a delay in heading occurred with approximately 5 lx of light. When the heading delay exceeded 10–15 days, the yield was greatly affected. Because we used data obtained from experiments, the representativeness of these results may be low. In the future, damage coefficients for assessing the ecosystem and human health should be developed.

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