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Light pollution as an ecological edge effect: Landscape ecological analysis of light pollution in protected areas in Korea

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ABSTRACT

Protected areas have been increasingly encroached upon by light pollution. This paper examines whether patch geometry and land development intensities in protected areas affect the light pollution levels in 22 Korean national parks. Light pollution levels were assessed based on mean nighttime radiance of these national parks derived from nighttime satellite images. Total floor areas of buildings in the parks and in a 1 km buffer zone outside the park boundaries were calculated to assess land development intensities both inside and surrounding the parks. Two landscape metrics (patch area and fractal dimension) were measured to assess the patch geometry of the parks. Results show that the mean nighttime radiances in the Korean national parks are significantly affected by total floor areas in the 1 km buffer zone, but not by the total floor area within the park. This suggests that skyglow caused by artificial light in periphery is a major source of light pollution in the Korean national parks. In other words, light pollution can be seen as an ecological edge effect in protected areas where land development is stringently restricted. This conclusion is also supported by significant effects of two patch geometry variables, i.e., light pollution was more severe in a protected area with smaller size and a more complex shape. Based on these findings, it is suggested to make protected areas larger and more simple-shaped to protect biodiversity from light pollution. Managing lights in periphery of protected areas is also suggested.

1. Introduction

Light pollution refers to a condition in which artificial light at night (ALAN) has an adverse effect on humans and ecosystems. Excessive light at night suppresses a person's melatonin secretions (Samanta, 2020; Socaciu et al., 2020; Touitou et al., 2017), resulting in insomnia (Min & Min, 2018), mood disorder (Obayashi et al., 2013), cardiovascular disease (Obayashi et al., 2019), and breast cancer (Lai et al., 2021; Lamphar et al., 2022; Wu et al., 2021).

Like humans, ecosystems are also damaged by light pollution's disruption of circadian and phenological cycles of wild animals (Gaston et al., 2013; Owen et al., 2020; Robert et al., 2015; Sanders et al., 2021; Svechkina et al., 2020). In lit areas, diurnal animals advance their circadian and reproductive cycles (Dominoni et al., 2013; Kempenaers et al., 2010; Kumar et al., 2018; Yorzinski et al., 2015). The extended duration of activity has both beneficial and deleterious effects on diurnal animals: some species enjoy more forage time under light (Gaston et al., 2013), while others suffer from less sleep time, which leads to various physiological problems (Jones et al., 2015; Navara & Nelson, 2007). The negative effects of light pollution are more prominent in nocturnal animals (Sanders et al., 2021; Senzaki et al., 2020). In lit areas, a bat community, for instance, changes its composition to favor species that forage for flying insects that are attracted to ALAN, but not to favor species that avoid lit areas due to the high predation risk (Azam et al., 2018; Haddock et al., 2019; Lacoeuilhe et al., 2014).

There is a growing concern about light pollution in protected areas (Barentine, 2019; Cho et al., 2014; Davies et al., 2016; Fan et al., 2019; Garrett et al., 2020; Gaston et al., 2015; Guetté et al., 2018; Li et al. 2020; Peregrym, Kabaš et al., 2020; Xiang & Tan, 2017). Light pollution is more severe in protected areas in proximity to large cities, because light is a pollutant that easily propagates into surrounding areas (Mcdonald et al., 2009; Navara & Nelson, 2007). Skyglow, a brightened sky caused by scattered light in the atmosphere, is another source of light pollution in protected areas in proximity to large cities (Buxton et al., 2020; Kyba et al., 2015; Sanchez de Miguel et al., 2020). This suggests that light pollution is an ecological edge effect that degrades habitat quality along the habitat edge (Haddock et al., 2019; Kempenaers et al., 2010; Korea National Park Research Institute, 2019).

Landscape ecology provides a solution to mitigate edge effects. A basic solution is to make a large and simple-shaped habitat patch

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because, given the same distance of an edge effect, the proportion of the area influenced by the edge effect is larger in a smaller and more complex-shaped patch than in a larger and more simple-shaped one (Dramstad et al., 1996; Ferrer-Sánchez et al., 2019; Shanahan et al., 2011). This leads to the hypothesis that the light pollution level in a protected area is affected by the area's size and shape.

The present study examined this hypothesis using light pollution levels in 22 Korean national parks of varying sizes and shapes. This study operationally defines light pollution as upward radiances from artificial light sources on the ground level that were detected by Visible Infrared Imaging Radiometer Suite (VIIRS) day and night band (DNB) nighttime images. Patch geometry and land development intensities inside and in the surrounding areas of the national parks were also measured to test the effect of landscape patterns light pollution levels in protected areas.

2. Material and methods

2.1. Study areas

The study sites were 22 national parks in South Korea (Fig. 1 and Table 1). Of the 22 parks, 16 are classified as International Union for the Conservation of Nature (IUCN) Category II protected areas, and the other six are classified as IUCN Category V protected areas (Korea National Park Service, 2020). The Category V parks are located in either major cities (Bukhansan, Gyeryongsan, and Mudeungsan), contain large ski resorts (Deogyusan and Taebaeksan), or are designated for protecting historical sites (Gyeongju). Of the 22 parks, three marine and coast parks (Hallyeohaesang, Taeanhaean, and Dadohaehaesang) and one peninsular park (Byeonsanbando) include both land and sea areas. Although the sea areas have some light sources (e.g., fishing boats), the numbers of light sources in sea are orders of magnitude less than those in land areas, and, hence, the sea areas of the four parks were excluded from the analysis. Excluding the sea areas, the total area of the 22 national parks under study is 3,972 km^2, which is 4.0% of the Korean terrestrial territory.

2.2. Nighttime images

Light pollution in the 22 national parks under study was assessed using the VCM version of the VIIRS DNB monthly nighttime images. The

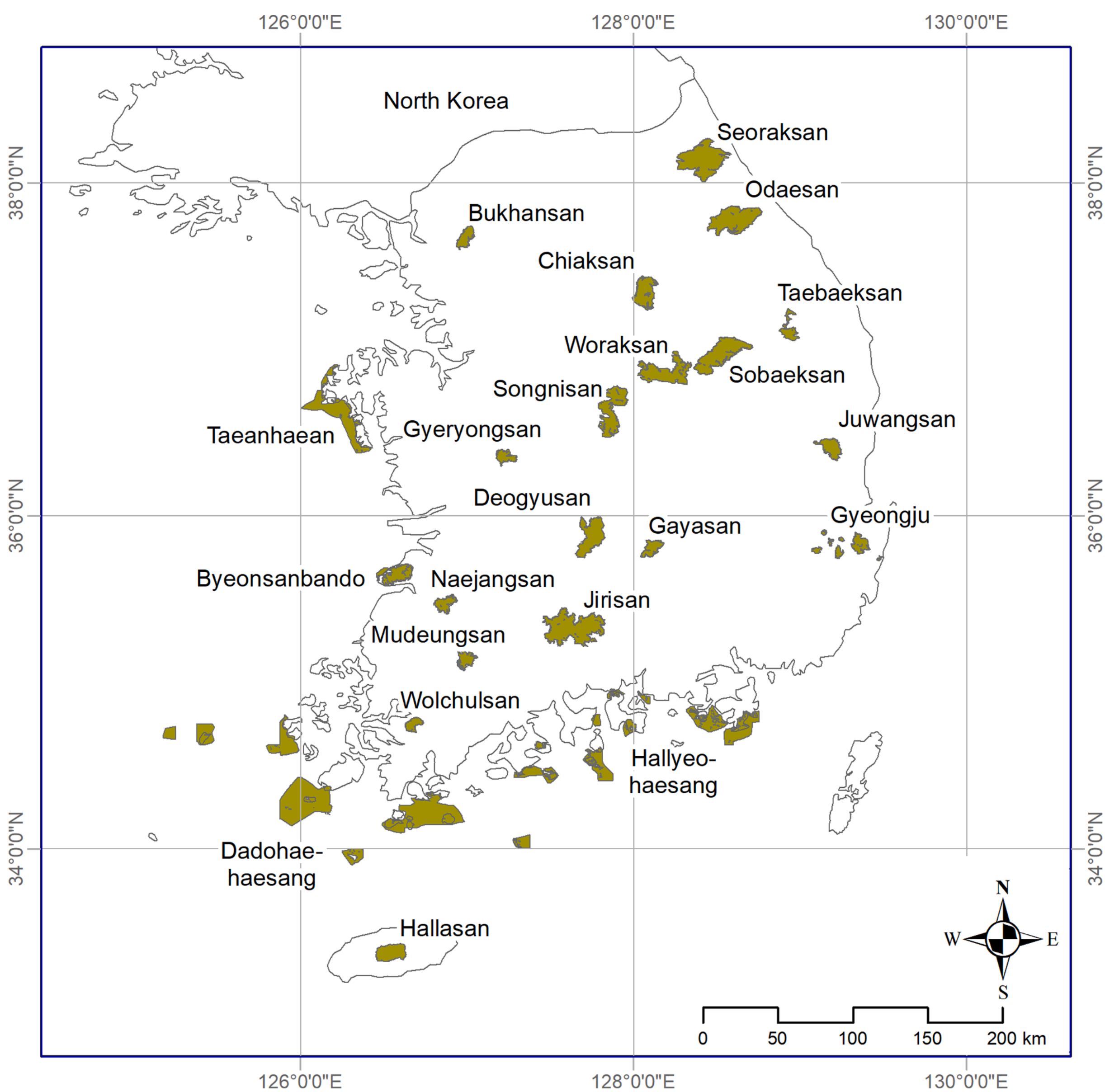

Fig. 1. A map showing the 22 Korean national parks under study.

Table 1
Basic information of 22 Korean national parks (Korea National Park Service, 2020).

National parks	Type	Year of foundation	IUCN category	Park area (km^2)	The average number of visitors in 2017–2019 (thousands/yr)
Jirisan	mountainous	1967	II	483.0	3,127
Gyeongju	historic	1968	V	136.6	2,945
Gyeryeongsan	mountainous	1968	V	65.3	1,830
Hallyeohaesang	marine & coastal	1968	II	535.7(land: 127.2)	6,642
Seoraksan	mountainous	1970	II	398.2	3,268
Songnisan	mountainous	1970	II	274.8	1,293
Hallasan	mountainous	1970	II	153.3	914
Naejangsan	mountainous	1971	II	80.7	1,986
Gayasan	mountainous	1972	II	76.3	729
Deogyusan	mountainous	1975	V	229.4	1,485
Odaesan	mountainous	1975	II	326.3	1,424
Juwangsan	mountainous	1976	II	105.6	1,177
Taeanhaean	marine & coastal	1978	II	377.0(land 24.2)	1,457
Dadohaehaesang	marine & coastal	1981	II	2,266.2(land 291.0)	2,196
Bukhansan	mountainous	1983	V	76.9	5,683
Chiaksan	mountainous	1984	II	175.7	723
Woraksan	mountainous	1984	II	287.6	724
Sobaeksan	mountainous	1987	II	322.0	1,192
Byeonsanbando	peninsular	1988	II	153.9(land 136.7)	1,690
Wolculusan	mountainous	1988	II	56.2	470
Mudeungsan	mountainous	2012	V	75.4	3,271
Taebaeksan	mountainous	2016	V	70.1	651

DNB is a panchromatic band (wavelengths of 500–900 nm) of the VIIRS sensor onboard the Suomi National Polar-Orbiting Partnership spacecraft (Elvidge et al., 2017). Its capacity for in-flight calibration and detection of low-level radiation at night, with a relatively high spatial and radiometric resolution, make this band popular in light pollution studies (Cheon & Kim, 2020; Garrett et al., 2020; Levin & Zhang, 2017; Xie et al., 2019), including studies on biodiversity conservation (Cho et al., 2014; Hu et al., 2018; Marcantonio et al., 2015; Peregrym, Kabaš et al., 2020; Peregrym, Kónya et al., 2020; Sung & Kim, 2020). The VIIRS DNB monthly nighttime images are composite images that average the radiance of moonless images collected each month. The VCM version further filters out stray light (Elvidge et al., 2017). The ground sampling distance of the composite images is 15 arc-seconds. To examine the seasonal variations in light pollution, this study used monthly composite images for January, April, August, and October taken between 2017 and 2019 (12 images in total).

Table 2
Descriptions of variables.

Variables	Descriptions (units)
Dependent variable	
Mean monthly nighttime radiance	ln [nighttime radiance in a national park (nW m^{-2} sr^{-1})]
Independent variables	
Park area	The area of the national park (km^2)
Fractal	$2(\ln P - \ln 2 - 0.5\ln\pi)/\ln A$ where P and A are the perimeter (km) and area (km^2) of a national park, respectively
Total floor area within the park	Sum of floor areas of all buildings within national park (km^2)
Total floor area within a 1 km buffer zone	Sum of floor areas of all buildings within a 1 km buffer zone from the park boundary (km^2)
The number of visitors	The monthly number of visitors to the national park (100,000 persons)

2.3. Variables

The purpose of this study is to explore whether patch geometry, land development intensity, and tourism activities influence light pollution levels in the national parks under study. For this purpose, this study performed multi-level model (MLM) analyses with light pollution in the parks as a dependent variable. Independent variables include two patch geometry variables, two land development intensity variables, and one tourism variable.

The mean monthly nighttime radiance in a park (an average of radiance values of VIIRS DNB pixels) was calculated to assess the light pollution level of the park (Table 2). Because this study conducted separate analyses for each season, mean monthly nighttime radiances were measured for each month under study. The calculated mean monthly nighttime radiance values were log-transformed owing to outliers in the dataset.

Path geometry variables included two patch-level (park-level) landscape metrics: park area and fractal dimension (Table 2). Fractal dimension D is a measure of how a patch boundary fills a plane. This metric is based on the idea that as a patch shape becomes complex, it fills more space. Fractal dimension is measured as a perimeter-area relation, $P \approx \sqrt{A^D}$ where P and A are the perimeter and area of the patch, respectively (Krummel et al., 1987; Mandelbrot, 1983; Milner, 1988). For a circle, $D = 2(\ln P - \ln 2 - 0.5\ln\pi)/\ln A$.

Land development intensities in a park were assessed based on total building floor areas (the sum of all floor areas in all buildings within the park, see Table 2). Floor area was used as a surrogate for nighttime radiances in the park. Land development intensities in the area surrounding a park were measured in the same fashion (i.e., the sum of all floor areas in all buildings within a 1 km buffer zone from the park boundary). The 1 km was selected as a buffer distance because the 1 km buffer from park boundaries cover all small gaps within parks that were formed to exclude traditional villages from national park areas. The 1 km buffers also cover most local villages and tourism facilities adjacent to the parks. Building floor areas were derived from building register data provided by the Korea National Spatial Data Infrastructure Portal (2018). Initially, the total length of roads was also considered as a measure of land development intensities but was not employed in the analysis, because many roads in the parks were unlit, and vehicles are prohibited on those roads at all times or certain times of the day or the year, which makes difficult to quantify them with respect to light pollution.

Besides land development intensities, visitors' activities could also contribute to nighttime radiance in a national park. To assess the potential impact of park visitors, the monthly numbers of visitors to each park as recorded by the Korea National Park Service (2020) were included in the analysis (Table 2).

2.4. Statistical analysis

This study examined the effects of the five independent variables on the mean nighttime radiance for Korean national parks by using MLMs. Four separate MLMs were built for each of the four study months to explore seasonal variations in the effects of the independent variables. Like a traditional regression model, an MLM investigates the causal relationship between independent and dependent variables, but it is applied to nested datasets that often violate the independence assumption (Gelman & Hill, 2007; Peugh, 2010). From the dataset used in this study, the mean monthly nighttime radiance was measured three times for each month, i.e., nested within the park level. Hence, this study built MLMs for a park as a random factor, and the five park-level independent variables as fixed factors. The MLMs were structured to be random intercept models, i.e., only intercepts were allowed to vary for each park, but slopes were not. Because residuals of the models did not meet the normality assumption, all statistical inferences were based on a bootstrapping procedure, a computationally expensive, nonparametric method that constructs confidence intervals of the parameters to be tested by using an empirical distribution estimated from a number of resampled datasets drawn from an original dataset (Efron, 1993). This study constructed bootstrapping confidence intervals of the five fixed factors using 9,999 resamples. The lme4 and sjstats packages from R were used for the MLMs (Bates et al., 2020; Lüdecke, 2021).

3. Results

3.1. Light pollution levels by park and season

Of the 22 national parks, light pollution was most severe in Bukhansan. The mean monthly nighttime radiance of this park was an order of magnitude higher than other parks in all seasons (Fig. 2). The incomparably high mean nighttime radiance in this park can be attributed to its proximity to the Seoul Capital Area with a population of 25 million. Numerous ALAN encompass this park from all directions. The next three brightest parks, Mudeungsan, Gyeryongsan, and Gyeongju, are also located in or near large cities. Four national parks in coastal areas (three marine and coastal parks and one peninsular park) were also relatively higher mean nighttime radiances than others. Unlike national parks in hilly mountains, those in coastal regions have long been used by people. Many harbors, shipyards, and fishing villages exist near those parks, which contaminated inside the national parks in coastal regions by light pollution (Caruana et al., 2020; Korea National Park Research Institute, 2019; Peregrym, Kónya et al., 2020).

Light pollution in the national parks has a seasonal pattern with highest mean nighttime radiances in winter (January) and lowest in summer (August) (Fig. 3). A bright winter is consistent with previous

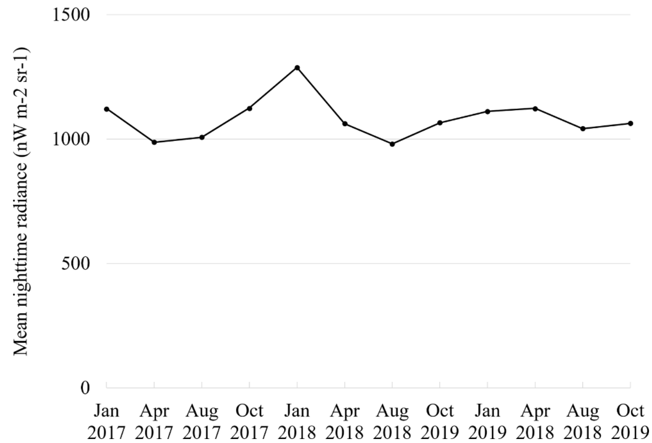

Fig. 3. Temporal trend of an average of mean monthly nighttime radiances.

studies (Levin, 2017) that found the positive effect of snow cover and negative effect of tree foliage on nighttime radiance, both of which increases surface albedo. Tree foliage also blocks lights from ALAN underneath canopy. Although a brighter winter was observed in most parks, the magnitude of relative brightness in winter varied from park to park. The two relatively brightest parks in winter were Taebaeksan and Deogyusan, where ski resorts are located (Fig. 2). The mean monthly nighttime radiance in January was 133% and 117% higher than the radiance in August for Taebaeksan and Deogyusan, respectively. One exception is Hallasan national park, where mean monthly nighttime radiance was lowest in the winter and highest in the summer. This opposite seasonal pattern for Hallasan national park can be attributed to its unique location on Jeju Island, a famous summer vacation destination in Korea. In 2019, visitors to Jeju Island were 25% higher in August than in January (Jeju Tourism Association, 2020). Hence, more light usage by island visitors can explain the higher light pollution level in Hallasan national park in the summer. The number of visitors to Hallasan National Park was also higher in the winter than in summer, but the numbers of visitors did not affect light pollution levels in the national parks under study for the reasons discussed next in Section 3.2.

There is no annual trend in nighttime radiances in the Korean national parks (Fig. 3), which is contrary to previous studies that reported continuous increases in light pollution as results of land developments and replacement of sodium vapor lamps to LED lights (Davies et al., 2016; Gaston et al., 2015; Guetté et al., 2018; Kyba et al., 2017; Li et al., 2020; Xu et al., 2019). This result implies that Korean national park system has been successful to regulate land developments. In fact, the Natural Parks Act prohibited land developments in national parks without permission of the park management agency. Transition to LED

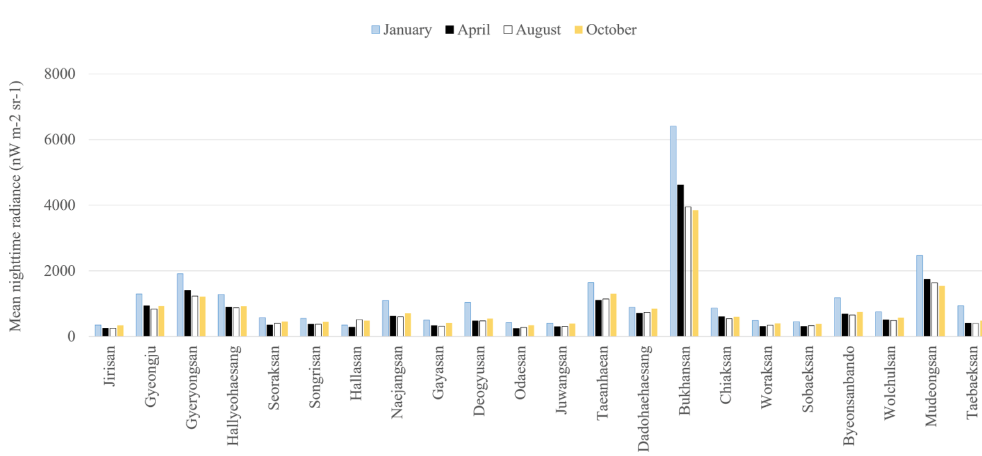

Fig. 2. Mean monthly nighttime radiances of the 22 Korean national parks.

lights is likely to occur in the study area, but not be captured in this study due to incapability of VIIRS DNB sensor of detecting shortwave radiance emitted from LED (Levin et al., 2020).

3.2. Effects of patch geometry, land development intensities, and tourism activities

The MLMs performed generally well. The five independent variables together explained more than 70% of the variations in nighttime radiances for all seasons (Table 3). The marginal R^2, a measure of the proportion of the variation explained by fixed factors only (Nakagawa & Schielzeth, 2013), was highest for the October model (0.800) and lowest for the January model (0.725), but the difference is not large.

Of the two land development intensity variables, the total floor area in the 1 km buffer zone has a statistically significant effect on the mean monthly nighttime radiances for all seasons, but not the total floor areas within the parks for any season at $\alpha = 0.05$ (Table 3). The effect of the total floor area in the 1 km buffer zone was significant even at $\alpha = 0.01$, indicating that light emitted from the park periphery is a critical factor for light pollution inside the park. The lack of impact of the total floor area within a park is somewhat surprising, but not unexpected, because strong land use regulations prohibit the construction of facilities that can bring light into the park. There are villages, roads, hotels and resorts, and even military bases in Korean national parks, but the overall land development intensities, i.e., the amounts of ALAN, were much lower in the parks than in any other regions of the country. Less ALAN within a park and the strong effect of light in the park periphery together suggest that skyglow created by light emitted from the park periphery is a major source of light pollution inside national parks. Similar results were also reported in previous studies (Buxton et al., 2020; Cho et al., 2014; Marcantonio et al., 2015; Xu et al., 2019).

The two patch geometry variables had a statistically significant effect on mean monthly nighttime radiances, but the magnitudes of the effects differed between the two variables (Table 3). The effects of park area were significant at $\alpha = 0.01$ for all seasons. The effects of park area were negative, meaning that the larger the park, the darker it is at night. The negative effects of park area were consistent with the theory of landscape ecology whereby a larger patch has better habitat quality because a smaller patch has more edge area that is affected by adverse effects from outside the patch. Given the finding that skyglow by ALAN in surrounding areas is a major contributor to light pollution in the park, the negative effects of park area support the research hypothesis that light pollution as an edge effect. Contrary to park area, the effects of fractal dimension were marginal and statistically significant only at $\alpha = 0.05$ for two out of four seasons (April and October). In terms of light pollution, April and October are two of the most typical seasons, when any special event that may affect light pollution levels does not occur in national parks. Without special events, the weak effects, like the effects of patch shape, were more likely to be detected. On the other hand, January and August are extraordinary seasons with various tourism events, e.g., ski slope operation and summer vacations, which potentially affect light pollution in the park. The effects of patch shape may be hidden by the effects of these extraordinary events.

The number of visitors to a park did not have a statistically significant influence on the mean nighttime radiance in any season. These results can be attributed to a curfew rule that prohibits visitors from entering Korean national parks after sunset. Under this rule, park visitors can stay only in designated places at night, like hotels and campgrounds. Hence, the effect of the number of visitors could be minimal in Korean national parks.

Table 3
Results of multilevel models for four seasons: (a) January, (b) April, (c) August, and (d) October. Single and double asterisks represent statistically significant effects of independent variables at $\alpha = 0.05$ and $\alpha = 0.01$, respectively.

Independent variables	Coefficients	95% confidence interval		99% confidence interval	
		lower bound	upper bound	lower bound	upper bound
(a) January (marginal $R^2 = 0.725$)					
Intercept	5.989				
Park area**	−0.002	−0.004	−0.001	−0.004	−0.001
Fractal	0.580	−0.009	1.154	−0.197	1.358
Total floor area in park	0.810	−0.332	1.910	−0.645	2.262
Total floor area in 1 km buffer zone**	0.075	0.043	0.107	0.033	0.118
The number of visitors	−0.016	−0.131	0.097	−0.164	0.128
(b) April (marginal $R^2 = 0.755$)					
Intercept	5.670				
Park area**	−0.002	−0.004	−0.001	−0.004	0.000
Fractal	0.653	0.074	1.236	−0.122	1.426
Total floor area in park	0.550	−0.487	1.606	−0.806	1.972
Total floor area in 1 km buffer zone**	0.077	0.046	0.108	0.036	0.118
The number of visitors	0.016	−0.054	0.085	−0.076	0.110
(c) August (marginal $R^2 = 0.730$)					
Intercept	5.921				
Park area**	−0.002	−0.004	−0.003	−0.001	−0.004
Fractal	0.515	−0.009	−0.060	1.090	−0.251
Total floor area in park	0.587	−0.332	−0.399	1.579	−0.717
Total floor area in 1 km buffer zone**	0.073	0.043	0.045	0.102	0.037
The number of visitors	0.000	−0.131	−0.061	0.063	−0.081
(d) October (marginal $R^2 = 0.800$)					
Intercept	5.939				
Park area**	0.000	−0.003	−0.001	−0.003	−0.001
Fractal	1.275	0.120	0.958	−0.026	1.085
Total floor area in park	1.901	−0.223	1.344	−0.455	1.577
Total floor area in 1 km buffer zone**	0.110	0.039	0.085	0.032	0.092
The number of visitors	0.083	−0.001	0.070	−0.028	0.083

4. Discussion

This study reveals that light pollution levels in a Korean national park are affected positively by land development intensity in the surrounding area, and are affected negatively by park area but positively by the park's shape. These results clearly support the research hypothesis that light pollution is an edge effect in a protected area that does not have light sources within its boundary.

Landscape ecology provides solutions to protecting habitat quality from edge effects. One of the solutions is to make a patch as large as possible (Dramstad et al., 1996). Although this approach is effective at mitigating edge effects, it could bring serious social conflicts with landowners if it involves the extension of a protected area into private properties. In fact, landowners' complaints are a great challenge in many protected areas around the world (Adams et al., 2011; Kim & Choi, 2017; Knight et al., 2011), including Korean national parks where 32% of the lands in national parks were privately owned (Korea National Park Service, 2020). Facing the landowners' complaints, the Korean government has been implementing a land acquisition program, but the budget covers purchasing less than 1% of private land per year. Hence, the making-a-large-patch approach must accompany other financial measures to resolve conflicts with landowners, e.g., tax incentives, compensation payments, and subsidies (Kamal et al., 2015).

Another solution to mitigating edge effects is to shape a patch as simply as possible (Dramstad et al., 1996). Many protected areas, including Korean national parks, have complex shapes because many of them are located in mountain regions where villages and farms sit along narrow valleys that cut into hilly landscapes. In these regions, protected-area boundaries are often delineated to exclude villages and farms, resulting in complex shapes. Then, the same problem arises (how to resolve conflicts with private landowners). In fact, many private lands formerly located inside protected areas have now been excluded from park areas due to landowners' complaints, forming small gaps in the protected areas. Often, these gaps are developed into hotels and campgrounds that are very effective at contaminating the inside habitat patches with light pollution. Considering the critical effects of the excluded areas, high priority should be given to these lands when the government implements a land acquisition program.

Maintaining the quality of a surrounding matrix is also a solution to mitigating edge effects (Driscoll et al., 2013). Most protected area systems focus on how to conserve habitat quality inside the protected area, but ignore the periphery. However, adverse effects from surrounding areas are major contributors that degrade the habitats inside protected areas (Ferrer-Sánchez et al., 2019; Shanahan et al., 2011). UNESCO's biosphere reserve provides a conservation scheme for managing the periphery of protected areas. The biosphere reserve is an international protected-area network that was proposed to reconcile ecosystem conservation and sustainable uses (Cuong et al., 2017). It consists of three tiers of protection zones. Core and buffer zones are where ecosystems are strictly protected, while a transition zone is designated in areas surrounding core and buffer zones, where local people are allowed to exploit resources up to sustainable level. Hence, community participation is essential for a transition zone to properly function as a protected area (Cuong et al., 2017; Stoll-Kleemann et al., 2010). To mitigate light pollution, a local community may voluntarily reduce lighting at night if a dark night benefits local tourism. For instance, a local community may consider operating darkness-themed eco-tourism programs, such as night-sky watching, firefly watching, and nocturnal animal listening (Sung & Kim, 2020). To succeed with these programs, a local community may be willing to reduce lighting times, and use cut-off lights and less bright bulbs. The protected area's managers can assist local communities by providing financial aid and technical assistance for light pollution-reduction measures.

5. Conclusion

Korean national parks, despites strict land development restrictions, suffer from light pollution. For Korean national parks where artificial lights are scarce, skyglow caused by ALAN in surrounding areas are the primary source of light pollution in the inside of the parks. A large park is less polluted by light because it has less edge area and more interior area that is not affected by edge effect. A complex-shaped park is more vulnerable to light pollution because the complex shape has a higher proportion of edge area. It can be concluded that making a protected area larger and more simple-shaped is needed to protect biodiversity from light pollution. Managing lights in periphery is also required to mitigate light pollution inside of protected areas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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