EXPLORING CANOPY CLOSURE OF FOREST TRAILS IN BUDDHIST TEMPLES USING HEMISPHERICAL PHOTOGRAPHY

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Abstract. The aim of this study is to explore light conditions under tree canopies and develop a logistic regression model based on the canopy structure of three forest trails in Buddhist temples located within the Gajisan Provincial Park of South Korea. Canopy structure variables related to light conditions under the canopy, including canopy openness, leaf area index, and solar radiation transmittance, were measured by digital hemispherical photography. Each point of photography, along with the center of the forest trail, had a gap distance of approximately 50 m. The characteristics of the canopy structure were expressed as 21% canopy openness, 1.79 m^2m^{-2} of leaf area index, and 29% solar radiation transmittance. The logistic regression model showed that there were significant effects of canopy factors in identifying Naewonsa temple against Seongnamsa temple. The model implied that the canopy structure of Naewonsa temple had a more center-concentrated canopy density with upright leaves, compared to those of Seongnamsa temple. Effective ways of using the forest trails of Buddhist temples were suggested regarding forest ecology and environmental management for the purpose of healing and ecotourism.
Keywords: *forest landscape, canopy cover, tree crown, ecotourism, applied ecology*

Introduction

Interests in ecotourism and nature-based healing, particularly through the Temple Stay Program in Buddhist temples, are increasing in South Korea due to the widespread recognition of forests as healing places (Lee, 2015). When conservation management of temple forests is required, the forest landscape concept provides grounds for the aesthetic value of the temple forest. Moreover, as a major factor in determining the landscape of the temple forest, a forest trail is important for both the ecological and utilisation aspects at the same time. The forest landscape inside the forest trail plays an important role in the appreciation of visitors towards trees around because many activities of visitors, such as walking, involve the temple forest. In this sense, an open landscape of the forest trail with suitable light conditions normally provides a good place for walking activities. The environmental factor that constitutes the landscape of the forest trail is largely determined by the light below the tree canopy.

The light environment beneath forest canopies can be highly variable in terms of time, space, and spectral quality, but it is primarily determined by the physical distribution of the tree canopy. The forest canopy is the highest vegetation surface that shapes the irregular contour of the upper tree crowns. It is composed of tree leaves, branches, fruits, and flowers as well as gaps between the tree crowns (Taureau et al., 2019). Many forest ecologists have attempted to analyse light conditions under the tree canopy, which has mainly been focused on the understory plants (Cannell and Grace, 1993).

The light conditions under the trees are affected by the canopy structure, which is approached by the concept of canopy cover and canopy closure (*Fig. 1*). Canopy cover is the perpendicular projection of tree crowns onto a horizontal surface (Tichy, 2016). It is

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the percentage ratio of ground cover by the vertical projection of tree crowns over the total ground cover. Canopy closure, on the other hand, is the proportion of the sky hemisphere obscured by canopy elements when viewed at a single point (Tichy, 2016). Canopy closure, viewed at a single point under the trees, is the ratio of the coverage of the look-up hemisphere made by the tree crown over the total ground cover. In the methodology, canopy cover is computed by analysing the data from satellite imagery or airborne photographs. On the other hand, canopy closure is measured by hand tools within a forest, which has the advantage of estimating the solar radiation factors under the tree canopy.

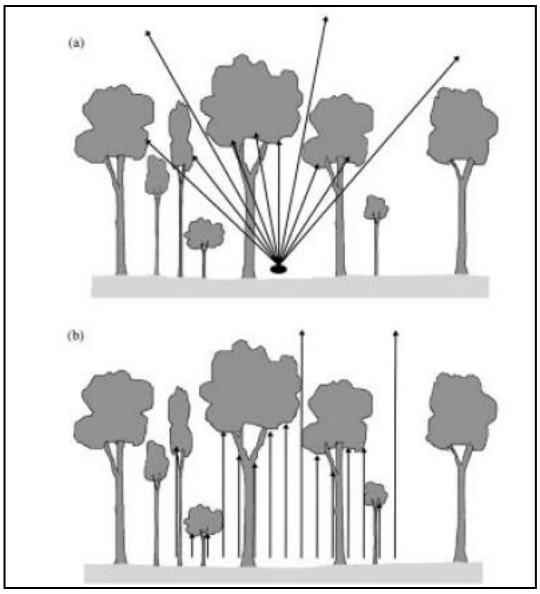

Figure 1. *(a) Canopy closure, (b) Canopy cover (Jennings et al., 1999)*

There are various methods for measuring light conditions under tree canopies, but many studies have used hemispherical photographs as a means to indirectly estimate canopy structure and the forest light environment (Cannell and Grace, 1993; Rich et al., 1993; Jennings et al., 1999). Hemispherical photography has been successfully used to study canopy structure and solar radiation regime. Hemispherical photography of the canopy is a technique for characterizing tree canopies using photographs taken through a camera with a fish-eye lens. Providing a means for direct measurement of canopy geometry is the primary strength of hemispherical photography (Rich, 1990). Hemispherical photography that directly measures canopy openness and indirectly estimates light levels is a potentially less expensive but time-consuming technique (Easter and Spies, 1994). Along with the development of application software for mobile phones in recent years, it is used either directly in field research or to analyze stored hemispherical photographs previously taken with a digital camera (Tichy, 2016).

In spite of the recent improvement in digital photography, some obstacles in the adoption of digital hemispherical photography of tree canopies still have to be pointed out (Chianucci and Cutini, 2012). Accurate and meaningful estimates of forest canopy properties with digital hemispherical photography are disturbed by different image acquisition, software processing, and so on. Adequate field collection and image processing procedures are required to obtain data using standardized digital devices

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(Chianucci and Cutini, 2012). Beckschafer et al. (2013) insisted that errors in hemispherical photography may arise from camera positioning and orientation, photographic exposure, and the discrimination of leaves from canopy openness. The modeled levels of incident and diffuse radiation are usually comparable with direct measurement in most forest conditions, but under the very dense canopy, the discrepancy could be bigger (Bolibok, 2010).

The photographs deliver two-dimensional images of the forest canopy in which both spectral and textural signatures are influenced not only by the optical properties but also by the distributional patterns of leaves, branches, and trunks (Taureau et al., 2019). Hemispherical photography is a multi-step process vulnerable to errors at each step (Beckschafer et al., 2013). The first step in processing hemispherical photographs is the photograph’s binarization. Exposure in hemispherical photography is not necessary to render the inner forest in great detail. Rather, exposure should aim at the correct and sharp depiction of canopy openings (Beckschafer et al., 2013). Macfarlane (2011) also insisted that the impact of binarization on the parameters of canopy openness from hemispherical photographs was not substantial.

The amount of leaf area in plant canopies influences primary production, transpiration, precipitation interception, microclimate, and energy, water, and carbon exchanges between vegetation and atmosphere (Pastorella and Paletto, 2013). A common measure of canopy foliage used in ecological studies is the Leaf Area Index (LAI), which can be defined as the amount of foliaged one-sided area in a canopy per unit of ground surface area (Pastorella and Paletto, 2013). The LAI, a key input to productivity models, can be estimated using a variety of remote sensing techniques. The canopy openness presents a challenge for evaluating canopy LAI and other biophysical parameters, as most remotely sensed methods were developed for homogeneous and closed canopies (Li et al., 2017).

The LAI is among the most important vegetation canopy parameters that can be estimated using hemispherical photography (Bolibok, 2010). The LAI is a canopy feature often measured by hemispherical photography so that it can be estimated with hemispherical photographs using some commercial and free software (Pastorella and Paletto, 2013). Many optical methods are already available to assess the canopy LAI. Because of the availability of affordable, high-resolution digital cameras and processing software, hemispherical photography is among the most widely used optical instruments and techniques applied for the description of canopy structure (Gonsamo et al., 2010). A variety of semi-automated and computerized techniques have been developed (Barrie et al., 1990; Smith and Somers, 1993; Walter and Torquebiau, 2000).

The modeling of light conditions under the canopy is another main application of hemispherical photography (Bolibok, 2010). A number of studies have shown the relationship between the estimates of solar radiation and canopy structures (Rich et al., 1993; Gendron et al., 1998; Engelbrecht and Herz, 2001). The availability of light in the forest understory is a limiting factor for plant survival and growth. The component of solar radiation used in photosynthesis is the photosynthetically active radiation (PAR). Light and PAR are often used synonymously because of their similar spectral ranges (Promis et al., 2012). The PAR is measured in terms of the total number or flux of quanta arriving per unit of time and expressed as photosynthetic photon flux density (PPFD).

A number of studies have demonstrated a high level of agreement between the measurement of forest understory light and both canopy structures and light transmission estimates from hemispherical photographs (Promis et al., 2012). Canopy openness can be used to estimate with accuracy the sum of the forest understory PPFD (Promis et al.,

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2012). Easter and Spies (1994) indicate that a close relationship exists for these forests between canopy openness, measured by hemispherical photographs, and measured PPFD. Compared to the method of using light sensors, in short, hemispherical photographic methods have advantages in cost-effectiveness, portability, and practicality for field survey in multiple sampling points (Machado and Reich, 1999). The aim of this study is to explore light conditions under tree canopy using hemispherical photography and to make a logistic regression model based on canopy structure of three forest trails of Buddhist temples in the Gajisan Provincial Park of South Korea.

Methods

Study area

Three forest trails in the Gajisan Provincial Park of South Korea, located in the southeast of the Korean peninsula, were chosen to compare light conditions under the canopy: Tongdosa temple (TD temple; 35.488068, 129.063715), Seongnamsa temple (SN temple; 35.621351, 129.032812), and Naewonsa temple (NW temple; 35.424243, 129.104517) (*Fig. 2*).

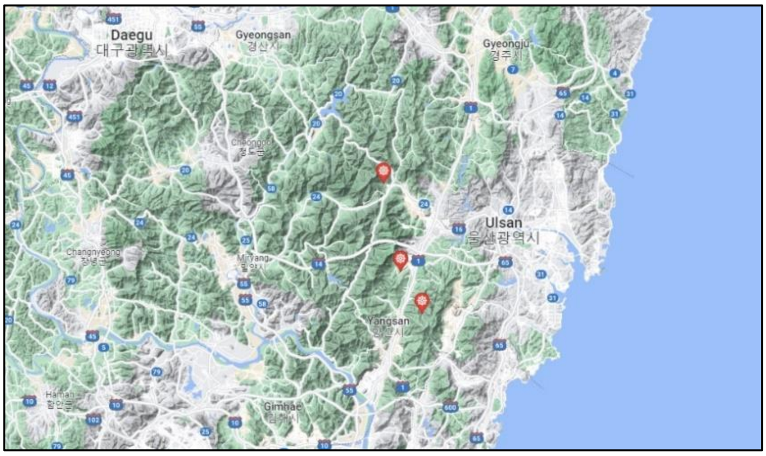

Figure 2. *Location of the survey sites*

The park, which was officially designated in 1979, includes high mountains around the region, such as Chuiseosan, Cheonseongsan, and Gajisan (Lee, 2015). TD temple, famous for its landscape of crag hills, is located on Chuiseosan mountain. SN temple is located on Gajisan mountain, which is the highest mountain in the region (1240 m) and is famous for its open view with grass grown on top of the mountain. NW temple is located on Cheonseongsan mountain, which is famous for its splendid landscape with valleys and small waterfalls. TD temple and NW temple were established in the year 646, and SN temple was established in the year 824. The temples possess religious and historical monuments, so public access to them has been prohibited since ancient times. In keeping with traditional Buddhist temples, the forest trails are well-conserved for moderate walking by monks. The forest types along the temple trails are temperate mixed forests dominated by *Pinus densiflora* in the upper story and by *Quercus mongolica* in the understory of the stand.

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Survey method

Canopy closure was measured at each site using hemispherical photography. The photographs were taken at the ground, considering the height of visitors to the forest trail. The length of each photograph was approximately 2.5 km, and the gap distance between each point of photography and the center of the forest trail was approximately 50 m. Trail characteristics, such as direction, width, altitude, and GPS waypoints, were recorded, as well as ecological characteristics such as the dominant tree species and uniqueness of the area. The survey was conducted from July 10th to 13th, 2019, under overcast skies to minimize the reflection of sunlight off leaves. Hemispherical photographs were taken using a Canon EOS 5D Mark II camera with Sigma 8 mm f3.5 fisheye lenses at a height of 1.4 m and arranged horizontally on a tripod. The camera settings were controlled automatically for aperture, shutter speed, and self-timer to obtain stable photographs of tree crowns. The digital camera featured a full-frame sensor with 21.1 million pixels and stored photographs as colour digital TIFF format without image compression.

Several software packages are available for the analysis of hemispherical photographs, including Gap Light Analyzer, WinScanopy, HemiView, and CANEYE (Beckschafer et al., 2013). In this study, the photographs were analyzed using the Gap Light Analyzer, which is specialized software for tree canopy analysis (Frazer et al., 1999). Gap Light Analyzer (GLA) is widely used in the scientific community to accurately measure forest canopy structure using hemispherical photography. However, accurately determining LAI can be challenging when there are overlapping leaves in the canopy. To address this issue, GLA offers an iterative method to estimate the LAI value that accounts for overlapping foliage, by adjusting the LAI value until the model-simulated transmittance matches the observed transmittance. In addition to LAI estimation, GLA provides various analysis capabilities, including calculating canopy openness, gap fraction, and LAI, even in cases of overlapping leaves.

Image analysis

The photographs were cropped into the rectangular type of hemispherical photographs based on a sub-circle of 60 degrees of zenith angle so that the boundary of the photographs was clearly defined, and the influence of underexposed areas near the horizon was minimized. The photographs, divided into 16 azimuth and 9 zenith regions, made a total of 144 sub-regions, which were used to calculate canopy closure (*Fig. 3*).

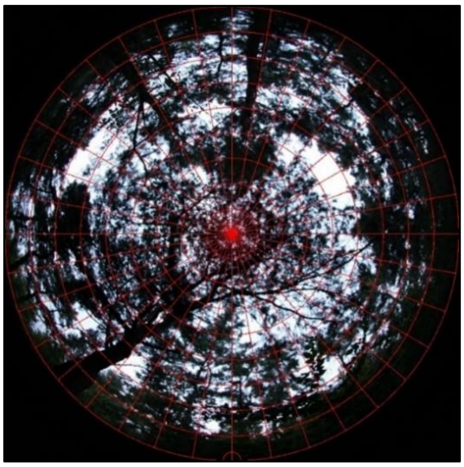

Figure 3. *Example of hemispherical photograph analysis*

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Modification of the color image to a black and white image was executed by the GLA software to separate the sky area from the tree canopy, based on the automatic threshold value from the edge detection method (Beckschafer et al., 2013). The Uniform Overcast Sky (UOC) method was applied to get a similar brightness value of a point in the sky at the zenith angle with that of the horizon. The GLA produced canopy structure variables such as canopy openness and effective LAI from the hemispherical photographs.

Canopy openness (OPN) was defined as the percentage of open sky seen from beneath a forest canopy (Frazer et al., 1999). The LAI was defined as the effective leaf area index integrated over the zenith angles 0 to 60 degrees (Frazer et al., 1999). The LAI was all covered area blocking sun light over total area, because the GLA did not discern opaque objects from plants. The GLA calculated LAI that was obtained from the gap fraction using the following formula (Promis et al., 2011) (*Eq. 1*):

$$L_e = 2\sum_{\theta_i=1}^{5} -ln(T_i)\, cos(\theta_i)\, W_i \qquad \text{(Eq.1)}$$

where:
θ_i is the five fixed viewing angles.
T_i is the gap fraction of each viewing angle.
W_i is the fixed weighted value of area correction.

Gap fraction, which was the fraction of open sky not blocked by the canopy, was used to calculate light-related canopy parameters obtained from hemispherical photographs. Exposure and sky illumination affected the estimation of all parameters associated with gap fraction (Zhao and He, 2016). In the binary hemispherical photographic image terminology used by Gonsamo et al. (2010), gap fraction was the ratio of the number of white pixels (e.g., background) to the total number of pixels (e.g., foreground). Gap fraction T_i was calculated given the zenith angle θ_i as follows (Promis et al., 2011) (*Eq. 2*).

$$\ln(T_i) = -K_{ij} \times L_i \qquad \text{(Eq.2)}$$

where:
T_i is the gap fraction at zenith angle θ_i.
K_{ij} is the extinction coefficient at zenith angle θ_i and leaf inclination angle α_j.
L_i is the LAI at zenith angle θ_i.

In addition, the GLA produced solar radiation variables such as solar radiation transmittances from the hemispherical photographs. Solar radiation transmittance (SRT) was the ratio of the total amount of solar radiation transmitted by canopy and topographic mask over the total amount of radiation incident on a horizontal or tilted surface taking into account the effect of a topographic mask, which was multiplied by 100% (Frazer et al., 1999). For the applied statistical approach, a one-way Analysis of Variance (ANOVA) with a 95% significance level was conducted to determine significant differences in OPN, LAI, and SRT among temple sites. Post-hoc analysis using the Scheffe test was performed thereafter. Also, logistic regression was performed to examine the effect of canopy structure factors (e.g., canopy structure and solar radiation) on the identification of temple sites along the forest trail.

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Results

Characteristics of canopy structure in temple forests

The results showed that the temple sites in the Gajisan Provincial Park had varying measurements of canopy structure and solar radiation (*Table 1*). The park overall had about 21% of OPN, 1.79m^{2}m^{-2} of LAI, and 29% of SRT. Among them, the NW temple had the highest OPN, the lowest LAI, and the highest SRT, followed by the TD temple and SN temple. Canopy closure of the research site, in other words, was generally dense at the level of 78%. The OPN of the TD temple was found to be at least 11.07% and a maximum of 38.27%, with an average value of 19.31%. The OPN of the SN temple was measured overall with an average of 16.06%, ranging from a minimum of 5.29% to a maximum of 25.93%. The OPN of the NW temple was at least 11.57%, a maximum of 60.90%, and an average OPN of 27.38%. It was considered that in the Gajisan Provincial Park, the SD temple had the highest dense canopy structure along the forest trail, followed by the TD temple and NW temple.

Table 1. *Characteristics of the canopy structure of the three sites*

Sites		OPN (%)	LAI (m^{2}m^{-2})	SRT (%)
TD temple	mean	19.314	1.859	26.889
	standard deviation	5.137	0.319	7.199
SN temple	mean	16.057	2.151	21.209
	standard deviation	3.935	0.423	5.998
NW temple	mean	27.383	1.359	38.493
	standard deviation	12.808	0.657	17.022
Differences between means	F-value	22.291	30.472	27.748
	significance	.000	.000	.000
	95% Min. range	19.299	1.690	26.605
	95% Max. range	22.537	1.889	31.123

The estimates of LAI were similar among sites, while the maximum LAI value differed significantly between SN temple and NW temple. One result showed that the LAI of TD temple was at least 1.06 m^{2}m^{-2} and the maximum was 2.54 m^{2}m^{-2}, with a mean of 1.86 m^{2}m^{-2} (*Table 1*). The LAI of SN temple was found to be at least 1.46 m^{2}m^{-2} and the maximum was 3.88 m^{2}m^{-2}, with an average value of 2.15 m^{2}m^{-2}. The LAI of NW temple was measured with an overall average of 1.36 m^{2}m^{-2}, ranging from a minimum of 0.07 m^{2}m^{-2} to a maximum of 2.46 m^{2}m^{-2}. The leaf area index of the forest trail in the Gajisan Provincial Park was 1.79 m^{2}m^{-2} in total, with the highest LAI observed in SN temple, followed by TD temple and NW temple.

Another result showed that the SRT of TD temple ranged from at least 15.55% to a maximum of 53.00%, with an average of 26.89% (*Table 1*). The SRT of SN temple was measured with an overall average of 21.21%, ranging from a minimum of 5.41% to a maximum of 36.10%. The highest SRT was observed at NW temple, with a minimum of 18.07%, maximum of 84.05%, and an average value of 38.49%. The mean value of SRT on the forest trail at the Gajisan Provincial Park was 29% in total, with the highest SRT observed at NW temple, followed by TD temple and SN temple.

The ANOVA test showed significant differences in OPN ($F=22.29$, $p<.001$), LAI ($F=30.47$, $p<.001$), and SRT ($F=27.75$, $p<.001$) among the sites (*Table 1*). Post-hoc

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analysis indicated that the NW temple had significantly different OPN values compared to the SN and TD temples. Significant differences in LAI were observed for each temple, and SRT also showed that the NW temple was significantly different from the SN and TD temples. In every aspect, the NW temple differed significantly from the other temples.

Statistical comparison of canopy structure in temple forests

The forest trails around the Buddhist temples are used by various types of visitors, which results in different canopy structures along the trails. A logistic regression model was efficiently applied to the forest trails based on the canopy structures of three different trails around Buddhist temples. To construct the regression model, a logistic analysis was performed using the total hemispherical photographs. As shown in *Table 2*, the probability of correctly classifying the temple site was 55.6%. The accuracy of premise classifications was 28.9% for TD temple, 37.0% for SN temple, and 34.1% for NW temple.

Table 2. *Probability of classification*

Classification		Predicted			Correctness
		TD	**SN**	**NW**	
Observed	TD	18	16	11	40.0%
	SN	9	29	7	64.4%
	NW	12	5	28	62.2%
	Total	28.9%	37.0%	34.1%	55.6%

The goodness of fit test for this study used the log-likelihood ratio. It was 235.586 with x^2=61.040 (d.f.=6, sig.<0.001), which was a reasonable value when the likelihood was high. The analytical model was confirmed to be appropriate. In addition, Cox-Snell R^2=0.364, Nagelkerke R^2=0.409, and McFadden R^2=0.206 showed sufficient explanatory power, and the independent variables set for the logistic regression analysis used in this study well explained the identification of temple sites. *Table 3* summarises the logistic regression analysis.

Table 3. *Logistic regression model*

Sites		β	S.E.	Wald	Sig.	Exp(β)
TD temple*	Const.	-5.847	4.499	1.689	.194	-
	OPN	.129	.106	1.462	.227	1.137
	LAI	2.877	1.565	3.379	.066	17.756
	SRT	-.056	.063	0.791	.374	.946
SN temple*	Const.	-9.378	5.658	2.747	.097	-
	OPN	.303	.136	4.988	.026	1.354
	LAI	4.741	1.856	6.529	.011	114.569
	SRT	-.193	.082	5.548	.019	.825

* compared to NW temple

The first logistic model comparing NW temple to TD temple showed that none of the independent variables - canopy openness, leaf area index, and solar radiation transmittance - had a significant effect on differentiating the temple sites between

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Naewonsa and Tongdosa temples. The second logistic model comparing the NW temple to the SN temple showed that all three dependent variables had a significant effect on identifying the temple sites between Naewonsa and Seongnamsa temples. Based on these results, the final logistic regression model was constructed and expressed as the following equation (*Eq. 3*):

$$\log\left(\frac{P_{NW}}{P_{SN}}\right) = -9.378 + 0.303\text{OPN} + 4.741\text{LAI} - 0.193\text{SRT} \quad \text{(Eq.3)}$$

In the model, the higher canopy openness, the higher leaf area index, and the lower solar radiation transmittance made the probability of identifying NW temple over SN temple higher. The environment of the forest trail beneath the tree canopy at the NW temple could be classified as an open canopy. However, the increase in LAI and the decrease in SRT indicated that the canopy density of the NW temple was more concentrated than that of the SN temple.

To confirm this, the odds ratio or multiplication ratio represented by exp(β) was used. If the level of canopy openness increased by one unit while controlling for other independent variables, the odds ratio became about 1.354. This means that the probability of identifying NW temple was 1.354 times larger than the probability of identifying SN temple based on a one unit increase in canopy openness. The percentage change of multiplication was 35.4%, meaning that if the level of canopy openness was higher by one unit, the probability of identifying NW temple compared to SN temple increased by about 35.4%. The exp(β) for statistically significant variables showed that the probability of identifying the temple site was about 1.146 times higher when the leaf area index (LAI) was increased by 0.01 units. When the level of LAI was higher by 0.01 units, the probability of identifying NW temple compared to SN temple increased by about 14.6%. The exp(β) of 0.825 for SRT indicated that a higher degree of solar radiation transmittance (SRT) lowered the probability of identifying NW temple compared to SN temple. When the level of SRT was higher by one unit, the probability of identifying NW temple over SN temple decreased by about 21.2% (=1/0.825).

Conclusions

The aim of this study is to explore light conditions under tree canopies and develop a logistic regression model based on the canopy structure of three forest trails in Buddhist temples located within the Gajisan Provincial Park of South Korea. Three canopy structure variables related to light conditions under the canopy, including canopy openness (OPN), leaf area index (LAI), and solar radiation transmittance (SRT), were measured using hemispherical photography. The characteristics of the canopy structures of the three forest trails can be summarized as follows.

Firstly, in terms of canopy closure, the forest trail of SN temple had the most dense forest canopy at 84%, followed by TD temple at 81% and NW temple at 73%. Secondly, the average LAI of the surveyed sites was 1.76 m^2m^{-2} in total, with the highest value at SN temple followed by TD temple and NW temple. Although LAI is a numerical value related to the vitality of the tree, it is difficult to directly compare with indices in a normal plant community since the basic characteristic of the forest trail of a Buddhist temple is a frequently used human area. Thirdly, the mean value of SRT of the forest trail was 29% in total, with the highest value at NW temple, followed by TD temple and SN temple.

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The ratio of solar radiation indicated that the amount of light reaching the forest trail of SN temple was the smallest when the forest canopy was well-formed.

Fourthly, the logistic regression model showed that the dependent variables, i.e., OPN, LAI, and SRT, had a significant effect in identifying the temple sites between SN and NW temple. Positive changes in OPN and LAI, and negative changes in SRT, made the probability of identifying NW temple over SN temple higher in the model. The logistic regression model explained the canopy structure of the temple trails based on the fact that, when leaves received a large amount of light, there was a tendency for the LAI to become larger if the canopy was composed of upright leaves. The landscape of the forest trail under the tree canopy at NW temple would be identified and characterized primarily as an open canopy. However, at the same time, positive changes in LAI and negative changes in SRT implied that the canopy structure of NW temple was rather a center-concentrated canopy density with upright leaves compared to those of SN temple.

The Buddhist temple located in Gajisan Provincial Park is a popular destination for ecotourists who typically pay an admission fee. To meet visitors' expectations, systematic management of the forest trails at the temple is necessary. As a historical cultural property, tourists are likely interested in sightseeing cultural heritage along with a well-maintained natural landscape that provides spiritual healing. Although the forest trails of all temples are in dense forest with above-average value, the canopy closure of NW temple is relatively low compared to other temples. Therefore, administrative efforts should be made to improve the vitality of the forest by supplementing trees along the forest trails and carrying out nursing efforts. Sustainable forest management techniques that improve forest productivity should be considered to achieve an ideal forest physiognomy.

The forest trail leading to the temple has been used for a long time, and trees along the trail have been cut at a low intensity as a method of forest management. To improve forest canopy structures for recreation and healing programs, it is suggested that the intensity level of cutting should be continuously controlled. Canopies have complex structures, and capturing multiple layers or irregular shapes of leaves accurately with hemispherical photography can be challenging. Weather conditions are important to capture accurate images of the canopy, and errors in estimates of canopy structures may result if these conditions are not optimal. There are also obstacles to using digital hemispherical photography for forest canopy analysis, such as image acquisition and processing procedures, standardized digital devices, and other factors. These limitations should be overcome and verified through rigorous field surveys.

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