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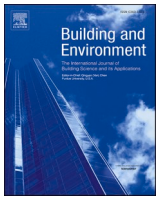
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Assessing the eco-centric light field to capture the light trespass of outdoor lighting

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ABSTRACT

Outdoor lighting supports human safety and visibility but also contributes to light pollution, which may disrupt ecological systems. This study applies an eco-centric lighting perspective, investigating the integration of three complementary lighting measurement methods using cubic light field measurements, vertical and horizontal illuminance, and luminance mapping. Three luminaire configurations, a conventional 4000 K road luminaire and two 2200 K alternatives (with and without louvre), were examined under varying environmental conditions (clear, cloudy, snowy clear and snowy cloudy). Measurements were conducted along a transect extending from the road into the adjacent terrain.

Our findings demonstrate that, when combined, the three measurement methods capture both the spatio-directional spread and diffuseness qualities on the pavement together with the distal effects of the lighting. Horizontal and vertical illuminance measurements revealed that the alternative luminaires reduced spill light into the terrain by up to 45 % compared to the conventional luminaire, with a further 16.6–19.5 % reduction achieved using a louvre. Cubic light field measurements quantified the spatial characteristics of light, showing that light vector magnitude declined rapidly within 3–4 m from the luminaire, and diffuseness drastically changed under snowy conditions with an increase of 112 %. Luminance mapping illustrated differences in contrast and relative visibility between luminaire types; overall, the conventional luminaire tended to stand out more against the background sky. This integrative approach enables a more nuanced understanding of how artificial lighting interacts with the surroundings and may contribute to the development of more eco-centric lighting strategies.

1. Introduction

Outdoor lighting has undergone radical changes during the last 150 years, significantly altering the way we live our lives -and the lives of other species around us. The positive effects of artificial light at night (ALAN) include increased visibility, safety, security, and enhanced aesthetics. It can enhance perceived safety for pedestrians, reduce the fear of crime, increase the use of outdoor facilities, beautify the surroundings, and even improve economic growth, according to Boyce [1]. However, ALAN also disrupts the balance of the natural cycles of light and dark, and light pollution is currently an increasing problem all over the world [2–4].

By limiting lighting design to solely human needs, we have come to a situation where other species' needs for a natural cycle from the darkness at night to daylight have been neglected [5–8]. An eco-centric lighting practice includes considerations of the composition of the electromagnetic spectrum, timing, intensity and light modulation, as well as the distribution of light [9] in both human and non-human perspectives. The light distribution highly impacts how objects and their surroundings appear, impacting human and non-human responses differently ("responses" includes human and animal vision but also other non-visual responses to radiation, of humans, animals, and flora). The light emitted by a road luminaire enhances visibility on the road and pavement, but a significant portion of it disperses into the surrounding environment [2]. This presents a problem with respect to both energy management and environmental sustainability. That is, light distribution management is important for enhancing visibility where it is needed and reducing the emission of light where it is unwanted. We studied the distribution of light in ecological conditions (from a luminaire and out into the terrain beside a footpath) using the light field method,

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conventional illuminance-based measurements and luminance maps to assess lighting quality and potential excessive illumination. We focused on human-centric light field metrics based on illuminance and luminance, including the light trespass in the terrain to capture side effects within that (human-vision-limited) range – for conventional and more eco-friendly illumination. So, we extended capturing the light field spatially, directionally, and holistically/integratively, but spectrally limited the study to the human range (for practical reasons).

2. Background

2.1. Anthropocentric lighting

Humans are a diurnal species, meaning that our sensory system is adapted to being mostly active in daylight. ALAN is allowing us to be active for greater parts of the day. Especially in the most northern and southern latitudes, where the sun doesn't rise for several months every winter or is only up for some hours, this is crucial. Artificial outdoor lighting addresses safety and productivity needs [1,10], but some argue that we have reached a point of a collective nyctophobia [11].

To quantify the light level, the most common type of measurement applied in practice is horizontal illuminance, capturing light incident from above. However, our perception of the lit environment is based on the light reaching the eyes after being reflected and scattered in the environment [12]. This distinction, between the measured horizontal illuminance and the light we actually experience, is crucial because the visual impression is formed by the three-dimensional light distribution and is influenced by many factors, such as the materials of the illuminated objects and surfaces, rather than only the light sources themselves [12,13].

The concept of the light field, originally introduced by Gershun [14] and later elaborated by Cuttle [15,16] and expanded scientifically within the Delft Lighting Design Framework [12], applies a more holistic approach for analysing and quantifying light. It defines luminance as a function of position and direction and captures the resulting lit environment shaped by both direct illumination and reflections from surrounding materials. The light field framework provides a scientific basis for lighting design principles. The qualities of the light field, that is, the amount and spectrum of the ambient or diffuse light, the amount, spectrum and direction of its focal or directed component, their ratio determining the light diffuseness [17,18], and the light texture properties [19]. This 5D function defines the appearance and modelling of the surroundings and objects in it [12,20]. Yu et al. described the 7D temporal and spectral characteristics of the light field [21,22]. Human visual perception depends on the spatial distribution of light, highlighting that diffuseness of light strongly influences how we perceive and navigate environments [23]. The diffuseness is influenced by both luminaire properties and environmental scattering – the latter even more so. In our study, we capture such effects and their influence on the resulting light in non-human inhabited areas next to the road.

2.2. Effects of ALAN on nature

A number of studies have shown the effects of lighting on organisms in nature [6,7,9,24–26]. In ecosystems, light is an important cue for most species' physiological and behavioural processes [27]. Jägerbrand and Spoelstra [6] claim that the progressive increase in artificial lighting has far-reaching consequences for most species and their ecosystems, and that the effects are highly variable and complex. To avoid the loss of biodiversity due to light pollution, keeping natural areas dark, limiting light emissions from near and distant light sources, and reducing sky brightness are of utmost importance [6]. Light pollution alters the habitats of birds [28–30], bats [31], small mammals [32,33], amphibians [34], plants [35], and insects [25].

Approximately 30 % of vertebrate species and 60 % of invertebrate species are nocturnal, making them particularly vulnerable to the impacts of artificial light at night. The effects of electromagnetic radiation on wildlife can be categorised into several distinct mechanisms, including temporal and spatial disorientation, attraction, desensitisation, and impaired recognition [30]. Recent research [36] shows that flying insects exhibit a dorsal light response, orienting toward the brightest part of their environment, typically the sky, in natural, unpolluted conditions. Artificial point light sources disrupt their orientation, altering attitude control across ten insect orders. The same study showed that light reflected from below caused a mismatch between the insects' sense of upward and the direction of gravity, causing the insect to crash on the surface. Fabian et al. [36] state that a nearby artificial light source shifts an insect's sense of vertical orientation, impairing its ability to maintain forward flight. They argue that the insects are not attracted to the light itself, but rather become entrapped around the light source, as they fly on trajectories orthogonal to the light source.

The distance at which moths are attracted to light varies from 3–130 m, depending on luminaire type, moon phase, moth family and background, thus the common street luminaires placed 30–50 m apart from each other will often create a barrier effect [37]. Migrating animals are affected by artificial light because many species orient using cues from the night sky [9]. For these species, skyglow can disrupt their navigation. Bird movement and distribution may be influenced by light from distances up to 5 km during migration periods [38]. Some bat species show negative responses to artificial light at distances up to 75 m [31,39].

The effects of ALAN on different species vary. According to Vasas et al. [40], each animal has a unique set of photoreceptors adapting to their ecological needs, and they are sensitive to different wavelengths and some species even to polarised light. Follestad [41] argues that the precautionary principle, namely, the adoption of preventive measures despite the lack of fully established evidence, should be applied to minimise potential negative effects. The European standard for road lighting, EN 13,201–02:2015, addresses the environmental effects of lighting through recommendations to minimise light emitted in directions where it is not necessary or desirable by using full cut-off luminaires and selecting an optical system or accessory to reduce the light in certain directions [42].

2.3. Eco-centric light fields

Biological impacts of light pollution occur even at light levels below 1 lx [43]. An eco-centric lighting practice incorporates the needs of wildlife and the ecosystem into the design. Outdoors, under open air, spill light disperses into the environment and sky, causing astronomical [44] and ecological light pollution [5], thus increasing a road's footprint, but often overlooked in risk assessments in building projects. Kocifaj et al. [45] argue that in urban management, determining the luminance and illuminance is necessary during the planning process, to account for scattering effects and nonideal construction of light fixtures, which can lead to light pollution [45] through various ways as skyglow, light trespass and glare [10]. Huge potential was found for a spatially tailored light distribution and shielding in a study from Germany [46], pointing out the importance of managing the light distribution as a part of eco-centric lighting approaches. Modern luminaires incorporate glare control, however, local light emission still affects ground habitats, and reflected light from the ground contributes to skyglow, as illustrated in Fig. 1.

Snow-covered roads reflect light much more than dry ones, and even after partial snow clearance, albedo levels remain 40–100 % above snow-free conditions [47]. Snow cover amplifies the upward radiative flux emitted, and modelling studies have revealed an approximately linear relationship between surface albedo and artificial sky brightness within and up to 30 km from urban centres [48].

Our study examines the light trespass, with particular attention to illuminance levels, both spatial (the light field) and horizontal illuminance, as well as the luminance observed from a distance [39]. We

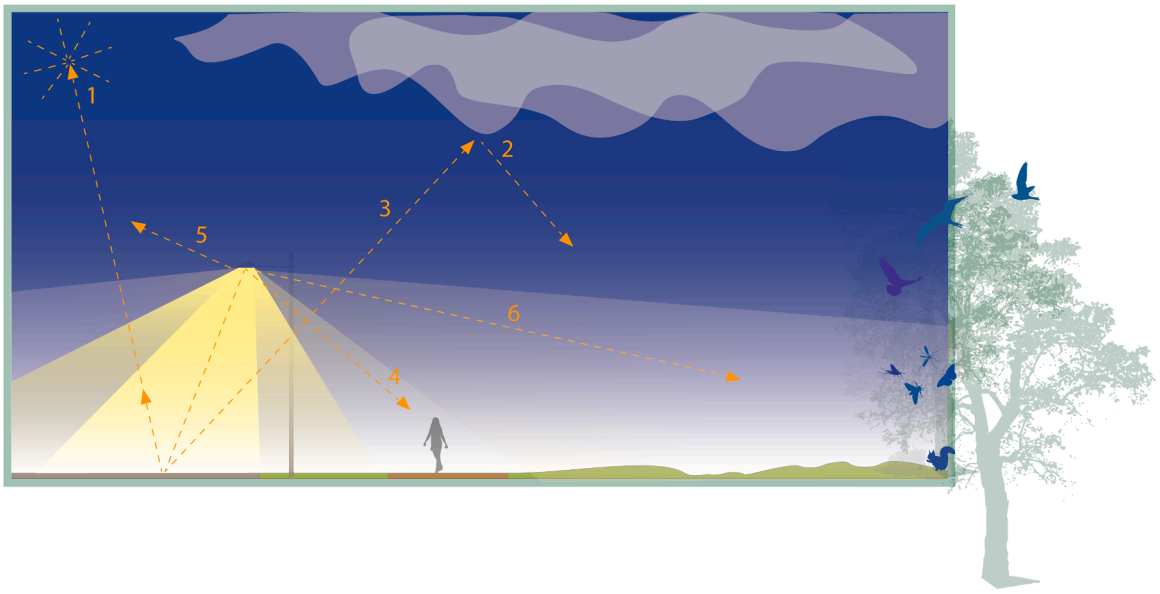


Fig. 1. Schematic illustration of light emission from a road luminaire: 1. Atmospheric scattering. 2. Scattering from clouds. 3. Upward reflected light. 4. Direct glare. 5 Direct upward light. 6. Light trespass. The primary luminous flux is directed towards the road and pavement, while a portion spills into adjacent areas, is reflected from the ground and surrounding surfaces, and is scattered by aerosols and clouds in the atmosphere, contributing to sky glow.

address the knowledge gap related to the balance between maintaining optimised pedestrian path illumination while minimising light spill into the surrounding environment, and highlighting the potential synergistic benefits of enhanced pavement lighting for the surrounding environment. A key question is how we can rapidly and practically capture the light trespass in the ecological terrain adjacent to a road, allowing us to measure and understand its spatial and directional impact through a field approach. Specifically, we investigated the use of cubic light field measurements to characterise illumination over the pavement and beyond, while exploring the combination of these measurements with horizontal and vertical illuminance measurements as well as luminance mapping in a transect stretching into the terrain beside the road. This approach was intended to test combined measurement procedures to evaluate the extent of light dispersion into the adjacent roadside area under the varying environmental conditions, snow and cloud cover, as well as to assess differences in illuminance levels among the three lighting configurations.

3. Materials and methods

3.1. Experimental design

The study was conducted beside a road and footpath in a rural area in Tønsberg municipality, Norway. The lighting system was installed on poles between the road lane and the pedestrian footpath, as is customary for such roads. The adjacent logging area is dominated by low vegetation, with few tall trees remaining (see Fig. 2).

Three distinct lighting configurations were used, each comprising four lampposts spaced 30 m apart (Fig. 2). The first configuration (Conventional) featured a conventional LED luminaire type for this road classification (Schreder Ampera; 4000 K, 14,000 lm, and 132 W), at 9 m height and 1 m bracket arm. The second configuration (Alternative 1) featured an alternative LED luminaire type (Thorn Isaro; 2200 K, 4820 lm, and 38 W), at 8 m height and 0,5 m bracket arm. The third configuration (Alternative 2) had an external louvre (glare shield, see Fig. 4) around the luminous aperture of the alternative luminaire (Thorn Isaro),

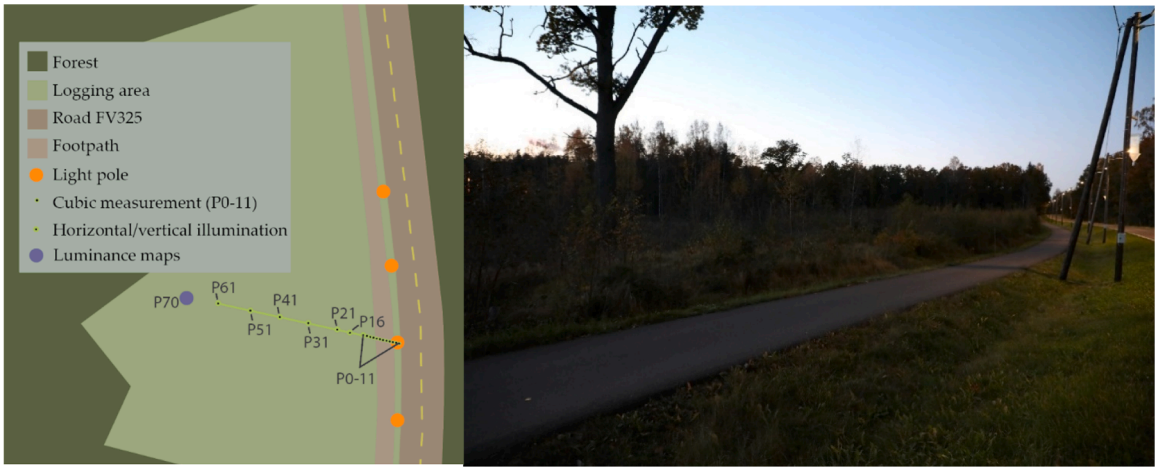


Fig. 2. Illustration of the measurement field (left) alongside a photograph (right) depicting the area in which the measurements were captured, the measured transect stretched from a point under the luminaire, beside the light pole, over the pavement and 61 m into the logging area. To avoid shadow from the light pole, the transect was not placed perpendicular to the road alignment. Luminance measurements were captured at P70.

all other parameters being the same (see Table 1). The conventional luminaire has a "Medium Road extensive" light distribution, and Alternatives 1 and 2 have "street comfort" light distribution (Fig. 3). The "Medium road extensive" type light distribution (Fig. 3) exhibits an asymmetric luminous intensity distribution with extended projection along the roadway. The 50 % luminous isointensity trace remains within approximately 1.5 to 1.75 times the mounting height on the street side relative to the luminaire position. Longitudinally, the 50 % trace extends to approximately 3 times the mounting height on both sides of the luminaire position, with the maximum candlepower located within this range. The Thorn Isaro luminaire, equipped with "Street comfort" optics, exhibits a compact luminous intensity distribution. The maximum luminous flux is located at vertical angles of approximately 55–65° from nadir, corresponding to a horizontal projection distance of approximately 1.7 to 2.2 times the mounting height in the plotted C-plane. The 50 % luminous flux level occurs at approximately 50–55° from nadir, corresponding to a projection distance of approximately 1.2 to 1.4 times the mounting height.

The alternative luminaire configurations are regarded as potential alternatives to the conventional type, which may reduce light pollution due to their lower luminous flux, narrower spectrum, and optimised light distribution with reduced lateral emission, thereby limiting light trespass toward the surrounding terrain. This study aimed to measure the effects of light, and thus, did not focus on luminaire design, nor guidelines related to this. The luminaires' power consumption was disregarded in this study.

In our study, the Conventional configuration corresponds to a standard luminaire type commonly implemented for roadways of this classification. Alternatives 1 and 2 are considered more eco-friendly alternatives with reduced luminous flux, lower CCT, and louvre (Alternative 2) (Fig. 4). Both luminaires were tested under overcast and clear skies, with and without snow cover, to evaluate the light dispersion into the adjacent roadside area under varying environmental conditions and lighting configurations.

3.2. Measurements

Light measurements were performed for three lighting configurations, Conventional, Alternative 1, and Alternative 2, under the different weather conditions, see Table 2. In the initial segment of the transect (P0 -P11), cubic measurements were captured at one-meter intervals (see Fig. 5). In the subsequent transect segment (P16-P61), horizontal and vertical (facing the road) illuminance was measured at 10 m intervals –here, the light levels were so low that cubic measurements were not considered meaningful. Thereafter, luminance images were taken in P70 (approximately 70 m from the luminaire) under selected conditions. It should be noted that data acquisition was logistically challenging due to terrain-related constraints and natural variability in weather and solar altitude over the two-year measurement period. The field site was overgrown and located at a considerable distance from both the university and the researcher's home, while all measurements had to be conducted at night. As a consequence, measurements under Clear, Cloudy, Snowy clear and Snowy cloudy conditions could only be obtained for a subset of the combinations in the matrix shown in Table 2 and are therefore treated as complementary.

Also, because of the seasonal variations in daylight, measurements were not possible from May to August, when the sun did not descend sufficiently below the horizon. All the measurements were performed when the sun altitude was 18° or lower below the horizon (astronomical night). Full moon was avoided, but in one weather condition (Clear), the moon lit up parts of the transect while measuring for the Alternative 2 luminaire.

Illuminance measurements were performed using the spectrometer Spectis 1.0 Touch + Flicker from GL Optics (Puszczykowo, Poland), equipped with a compatible Salli diffusor, to enable accurate readings at low light conditions at night (below 10 lx). For cubic measurements, the light meter was sequentially oriented on the six faces of a gauge cube (see Fig. 6), positioned at a height of 1.5 m above the ground at the measurement points P0 to P11. For horizontal and vertical illuminance measurements on P 16 -P61, the same gauge cube was used, but only two directions were included in measurements, i.e. horizontal facing upwards and vertical, facing the road.

The luminance images were captured using an LMK 6 luminance camera (TechnoTeam, Ilmenau, Germany), calibrated with a V(λ) and equipped with a 25 mm lens using the High Dynamic Range function.

3.3. Analysis

From the cubic illuminance measurements, the light field [17,18,22,49], was calculated using Mathematica 13.3, to determine light density (mean illuminance at a point, (E_{scalar})), light diffuseness (D), symmetric illuminance (∼E), the light vector components (E_x, E_y, E_z) and its magnitude (|E|), vertical illuminance (E_{x+}), and horizontal illuminance (E_{z+}) using the following equations:

$$E_{(x)} = E_{x+} - E_{x-} \tag{1}$$

$$|E| = \sqrt{E_{(x)}^2 + E_{(y)}^2 + E_{(z)}^2} \tag{2}$$

$$\sim E_x = \frac{E_{x+} + E_{x-} - |E_{(x)}|}{2} \tag{3}$$

$$\sim E = \frac{\sim E_x + \sim E_x + \sim E_x}{3} \tag{4}$$

$$E_{scalar} = \frac{|E|}{4} + \sim E \tag{5}$$

$$D = 1 - \frac{|E|}{4E_{scalar}} \tag{6}$$

Luminance images were processed using the LabSoft 4 software. Luminance and luminance contrasts were evaluated through comparison of the selected regions around the luminaires and the terrain along the road (Fig. 14). At 70 m distance (P70), three luminaires (Luminaire 1–3) were captured within the field of view of the luminance camera. Six measurement regions (equally sized for each image) were created: around luminaires 1–3, whole image, terrain/ground, sky and an area along the road (see Fig. 14).

For the selected areas, the fifth and ninety-fifth percentiles, median, mean, maximum, minimum and standard deviation values were obtained from the luminance histograms. The resulting values were compared among different luminaire types as well as weather conditions.

Table 1
Parameters of the lighting configurations used in the study.

Light configuration	CCT (K)	CRI	Lumen output	Light distribution	Power (W)	Distance between poles (m)	Mounting height (m)	Bracket arm (cm)	Distance from road (cm)	Additional louvre
1. Conventional	4000 K	>70	14 000	Medium road extensive	132	30	9	100	50	No
2. Alternative 1	2200 K	>70	4820	Street comfort	38	30	8	50	50	No
3. Alternative 2	2200K	>70	4820	Street comfort	38	30	8	50	50	Yes

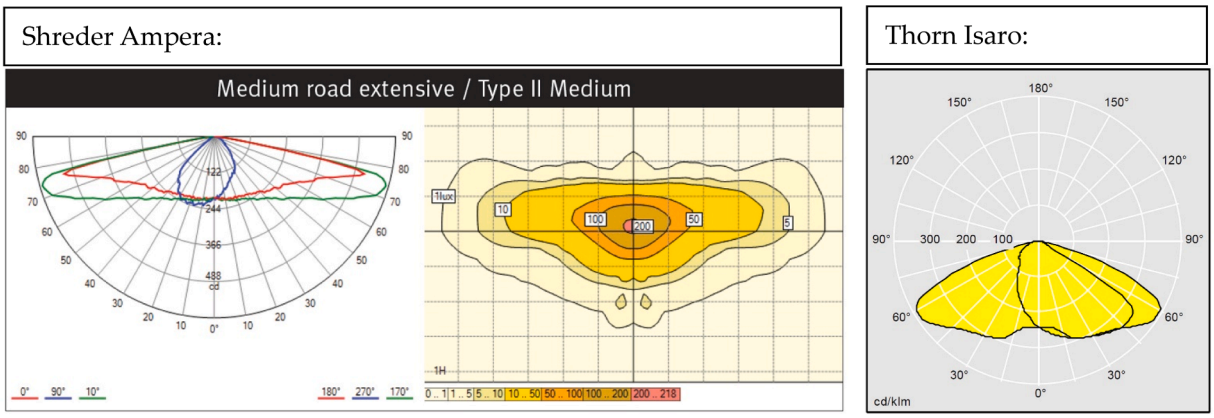


Fig. 3. Polar diagrams for the conventional luminaire (Schreder Ampera) with "medium road extensive"-type at the left and for alternative 1 and 2 (Thorn Isaro) with "street comfort"-type at the right (diagrams: Schreder and Thorn Lighting).



Fig. 4. The louvre installed at the Alternative 2 luminaire (photo: Thorn Lighting).

Table 2
Luminance (L) and illuminance (E) were measured for the three lighting configurations under four different weather/surface conditions: clear, cloudy, snowy clear, snowy cloudy.

	Conventional	Alternative 1	Alternative 2
Clear	$E + L$	$E + L$	$E + L$
Cloudy	E	E	
Snowy clear	$E + L$	E	$E + L$
Snowy cloudy	E		E

4. Results

4.1. Illuminance measurements

Measurements demonstrate differing fall-off profiles of illuminance with distance from the luminaire into the adjacent terrain for the three luminaire types. Fig. 7 shows the horizontal illumination as a function of distance from the luminaires (logarithmic scale), with each graph representing one lighting configuration. Please note that dots correspond to measurement position numbers, and the x-axis indicates the distance from the luminaire. As expected, the fall-off for all profiles is close to linear for the first 10 to 15 m. After that, the values saturate at a level that is dependent on the weather conditions. Mean horizontal illuminance values for the whole transect averaged across all weather conditions (Fig. 7) showed that the Alternative 1 luminaire produced 45 % lower mean horizontal illuminance compared to the Conventional one. Alternative 2 luminaire (with louvre) further reduced the mean horizontal illuminance by 16.6 %. This shows that the environmentally friendly luminaires significantly reduce spill light on the terrain beside the road, and their effectiveness improves even further with louvres. Percentage reductions were calculated relative to the mean horizontal illuminance produced by the Conventional luminaire, which served as the reference condition.

Fig. 7 clearly shows the influence of environmental conditions on horizontal illuminance. This effect is observable at 20 m distance and further. This observation is relevant for each luminaire type. Compared to the Clear condition (across three lighting configurations), horizontal illuminance was 39 % higher under Cloudy conditions, 116 % higher under Snowy clear conditions, and 350 % higher under Snowy cloudy conditions. Interestingly, for the Clear conditions and the shielded luminaire (Alternative 2), our measurements showed that a visible full moon at distances greater than 30 m increased illuminance to levels comparable to those of the Conventional luminaire (Fig. 8). Here, both the Conventional and Alternative 2 luminaire reached 0.2 lx at P51 and P61, whereas the unshielded Alternative 1 measured 0.1 lx.

Vertical illuminance (Fig. 9) followed a similar pattern as horizontal illuminance, but with lower levels observed under the luminaire and peak values occurring approximately 2–3 m away. For vertical illuminance, the reduction of illumination between the Conventional and Alternative 1 was 55 %, with a further decrease of 19.5 % for the luminaire with louvres.

Fig. 10 presents the values for all conditions, plotted together, for the three luminaire configurations under both horizontal and vertical illumination. The plots illustrate the impact of each luminaire type on the first segment of the transect. At greater distances, the light levels are so low that the effects overlap and become harder to represent in these plots, while in Fig. 7, the effects at greater distances are easier to distinguish.

Fig. 11 shows the plots for Light vector magnitude and diffuseness for two conditions, to visualise the change over the transect. The light vector magnitude reached levels of 35 - 72 lx near the luminaire and declined rapidly to levels between 2 and 16 lx at distances of 4–7 m, corresponding to the pavement area (the pink shaded area in Fig. 11). It varied across luminaire types, as expected, and between weather conditions. Under Snowy clear conditions, the difference between conventional and Alternative 1 was 46 %, and between Alternative 1 and 2, the difference was 23 %, suggesting that both luminous flux and louvre contribute to variations in light vector magnitude.

The light diffuseness (where 1 is fully diffuse and 0 is fully collimated) indicated a clear influence of scattering properties (snow and cloud cover) of the surrounding environment on diffuseness levels

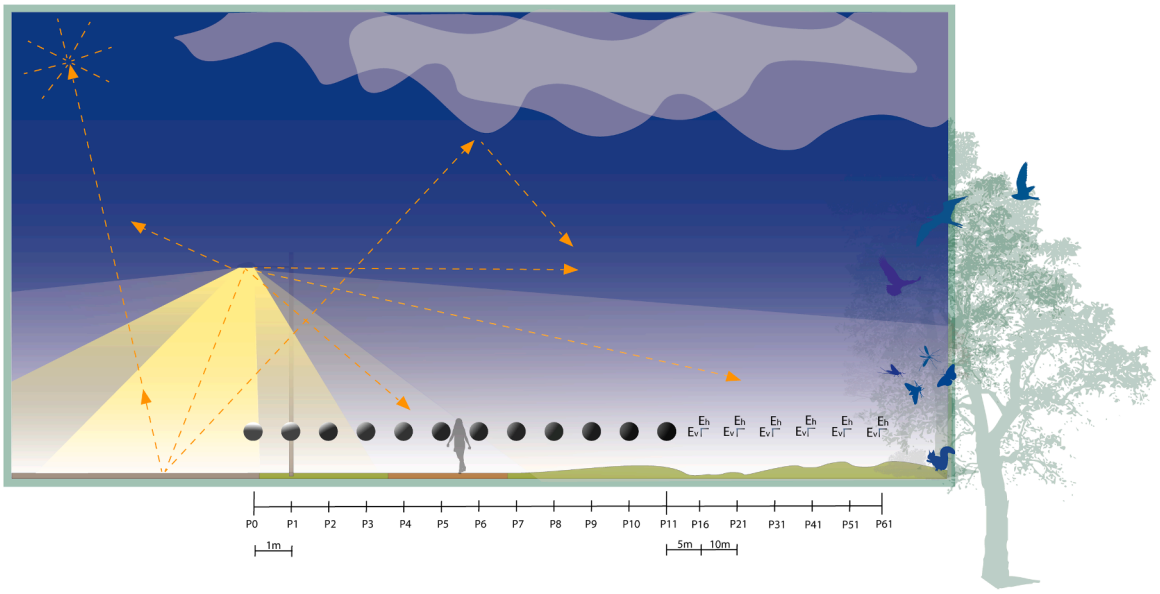


Fig. 5. shows the positions for the light field measurements (P0-P11) and horizontal and vertical illuminance measurements in positions 16–61. Spheres show an example of renderings based on light field measurements, and how they change at the varying distances from the luminaire, across the footpath and into the terrain.

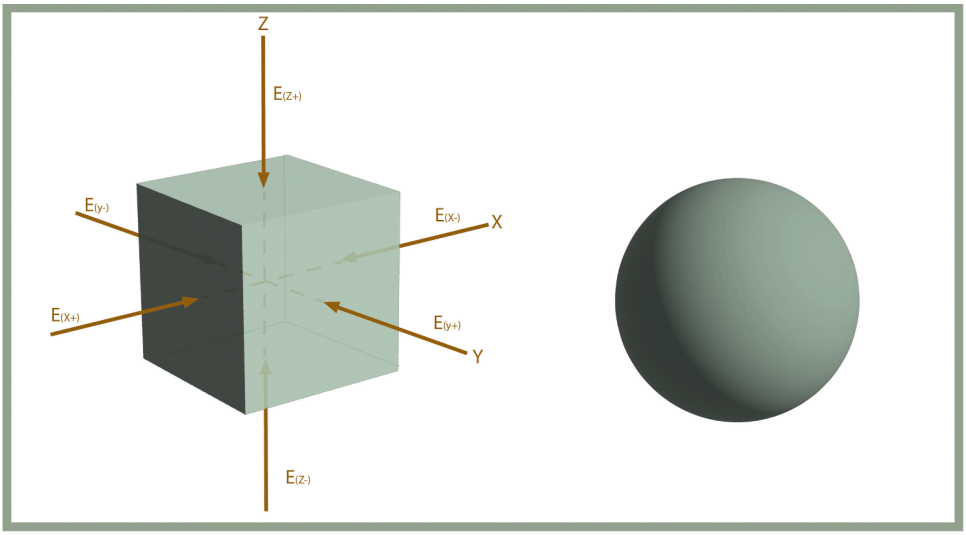


Fig. 6. Cubic light measurements: illuminance measurements were captured at each plane of a cube, here with a representation of a matte sphere in this specific local light field [17].

(Fig. 12). The average diffuseness for Clear conditions was 0.3, and for Cloudy it was 0.27. For Snowy clear and Snowy cloudy conditions, the diffuseness levels increased by 112 % to 0.64 and by 85 % to 0.56, respectively, relative to the Clear condition. Snow cover substantially increased the diffuseness of the light to 0.6–0.8 over the pavement (4–7 m). Diffuseness tended to increase with distance, under Clear and Cloudy conditions, values ranged from 0.1–0.3 near the luminaire and increased with distance, reaching 0.2–0.4 over the pavement (4–7 m), though this effect was also influenced by snow and cloud conditions. For Snowy conditions, diffuseness values near the luminaire ranged from 0.3–0.6 and increased to approximately 0.6–0.8 over the pavement region.

Sphere renderings in Fig. 13 were visualised based on the cubic light measurements and show how the light qualities vary as a function of distance across different luminaires and weather conditions. Rows 1, 2, 3 represent computer-rendered matte white spheres at the locations of the cubic illuminance measurements, on a blue background, for visibility. See [21,49,50] for the technical background. Row 1 shows the simulation under just the mathematical first-order component of the lighting, the light vector or directed part of the light. Row 2 shows the simulation for just the symmetric component of the diffuse component of the light. Row 3 shows the combined result or “appearance". For each row, we tone-mapped the rendering results such that they covered the maximum range possible in print (black to white). Please note that the real luminance values cover a much wider dynamic range.

Clear conditions produce more directional lighting, while diffuseness is clearly higher for the Snowy cloudy conditions. For Alternative 2, the contribution of the direct illumination from the luminaire decreases more rapidly along the transect than for Conventional.

4.2. Luminance measurements

Analysis of the luminance maps was performed through comparison and contrast calculation of the following regions shown in Fig. 15:

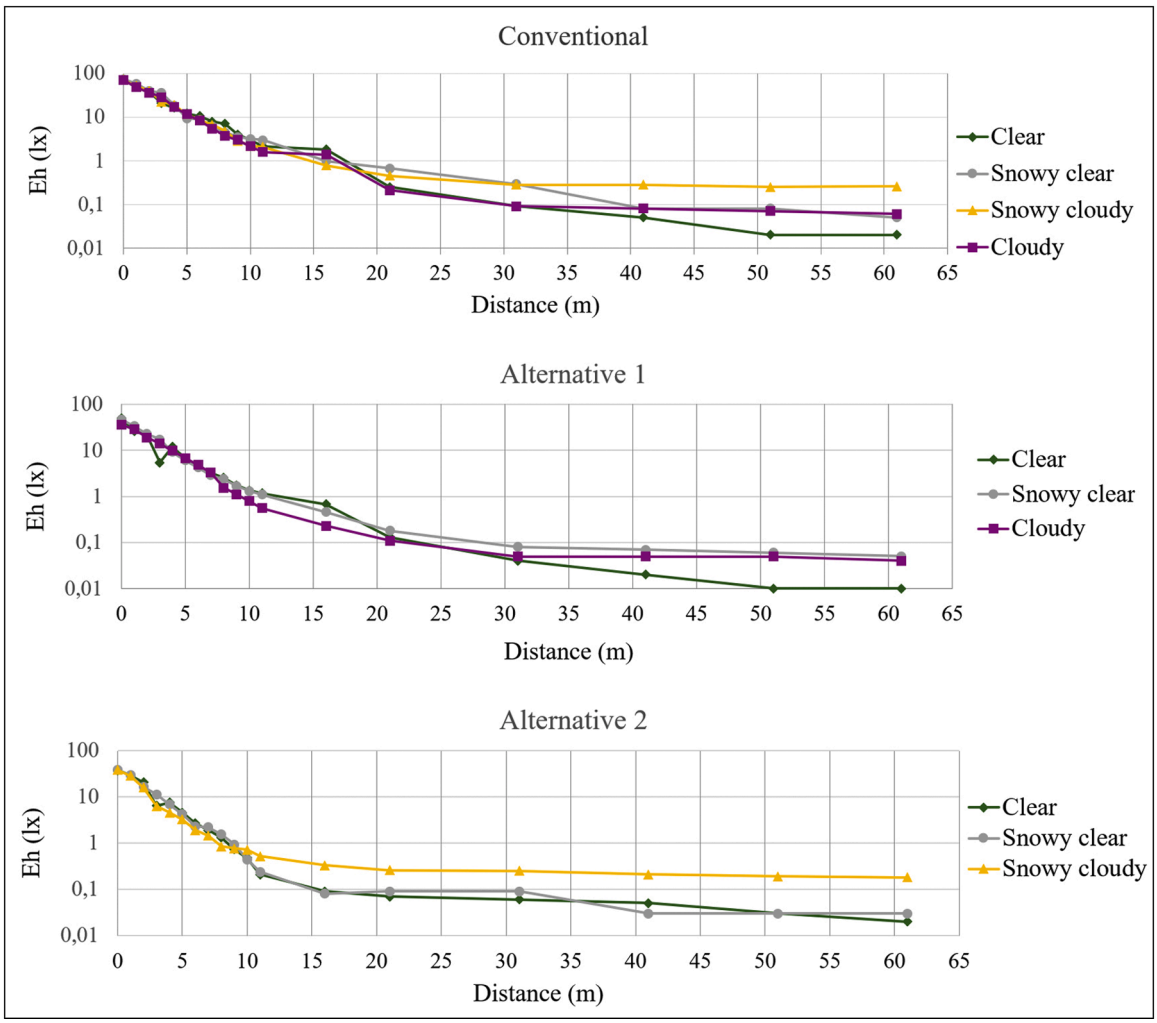


Fig. 7. Horizontal illuminance (lx) as a function of distance from the luminaire under the different conditions (clear, snowy clear, snowy cloudy, and cloudy) plotted on a logarithmic scale.

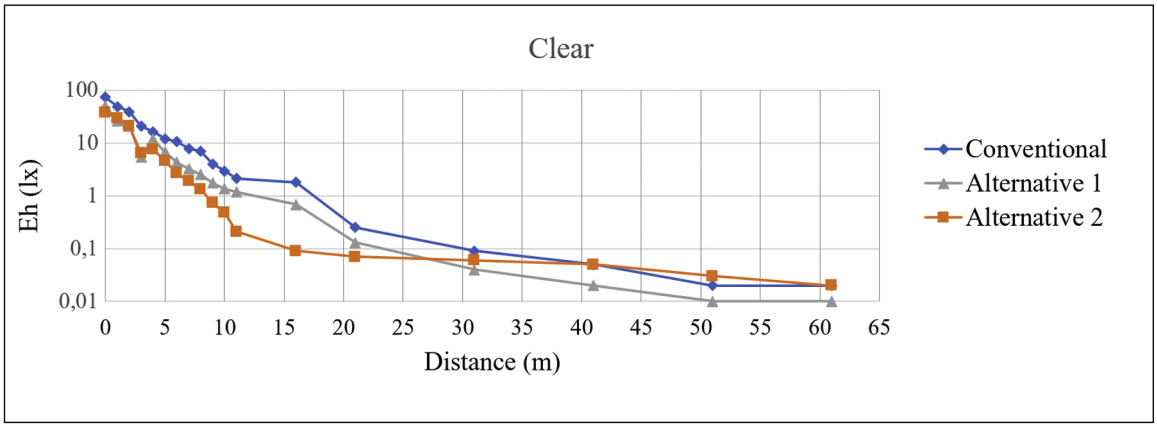


Fig. 8. Horizontal illuminance measurements under the clear condition. plotted on a logarithmic scale.

circular regions 1–3 representing light distribution around the luminaire, region 4 covers a portion of the terrain, region 5 covers a selection of the sky, and region 6 encompasses the area across the road and its surroundings. Comparison showed that the mean luminance of the selected terrain area without snow (region 4 in Fig. 15, A, C, D) decreased by 13.9 % when lit by the Alternative 1 luminaire compared to the Conventional luminaire, and by 25.3 % when lit by the Alternative 2 luminaire. Comparing no snow and snowy conditions (region 4 in Fig. 15, A-E), the overall luminance levels increased by 81 % for the Conventional and 84 % for the Alternative 2 luminaire, showing a significant impact of the reflective properties of the environment. Although the Conventional luminaire was expected to yield consistently higher luminance values than Alternatives 1 and 2, this pattern did not hold across all measurements taken when comparing luminance values

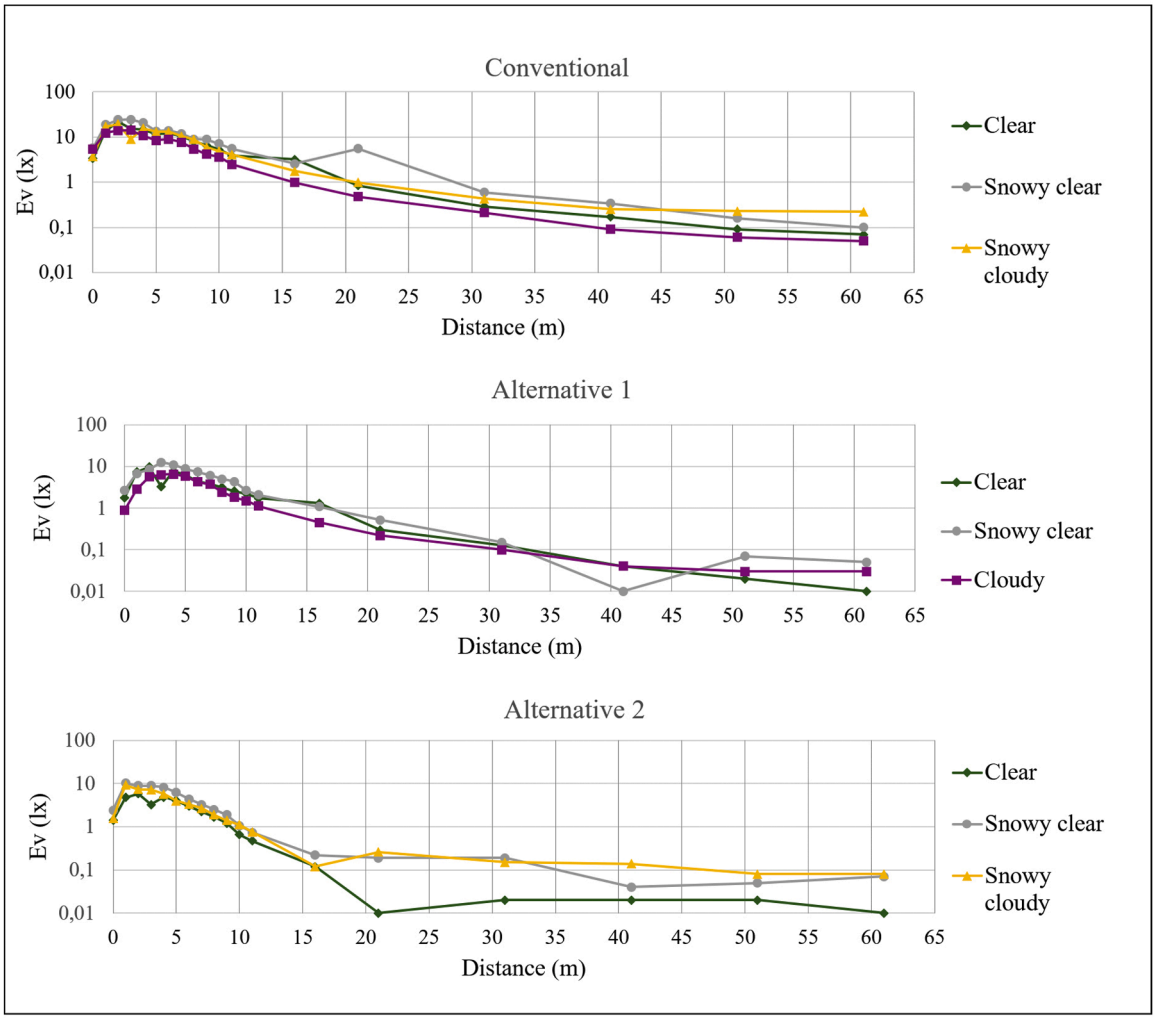


Fig. 9. Vertical illuminance (lx) as a function of distance from the luminaire under the different conditions (clear, snowy clear, snowy cloudy, and cloudy). plotted on a logarithmic scale.

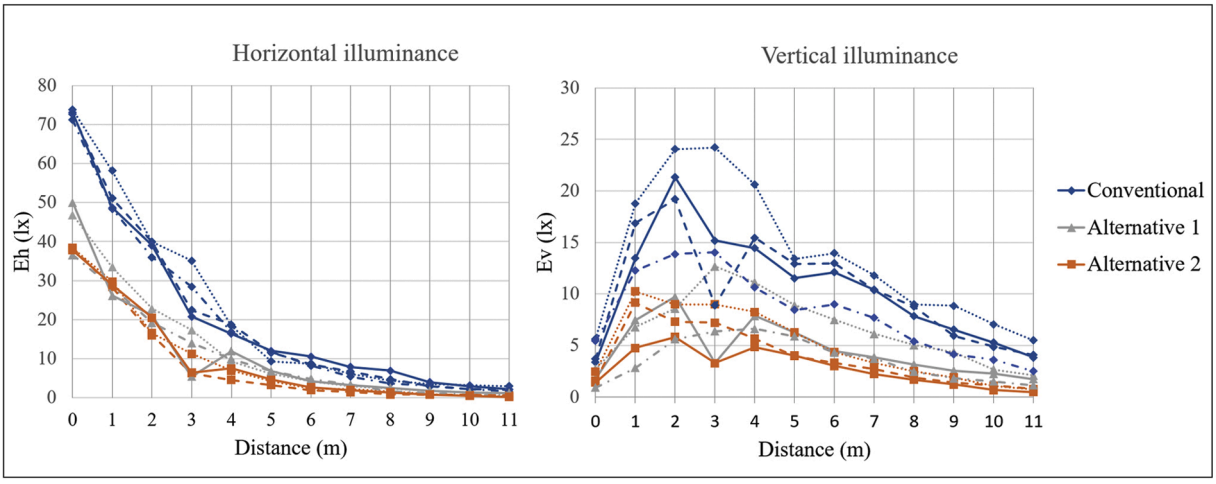


Fig. 10. Horizontal and vertical illuminance for the three luminaire configurations with combined results for each luminaire. All atmospheric conditions are plotted for each luminaire type, with a drawn line corresponding to clear, a dotted line to Snow.

measured in regions 1–6. These inconsistencies may be attributed to luminous overflow, sensor saturation or blooming from excessively bright areas that exceed the camera's dynamic range and introduce distortion into the luminance measurements [51]. Consequently, the luminance data were considered insufficient to draw definitive conclusions regarding the comparative performance of the luminaires. In

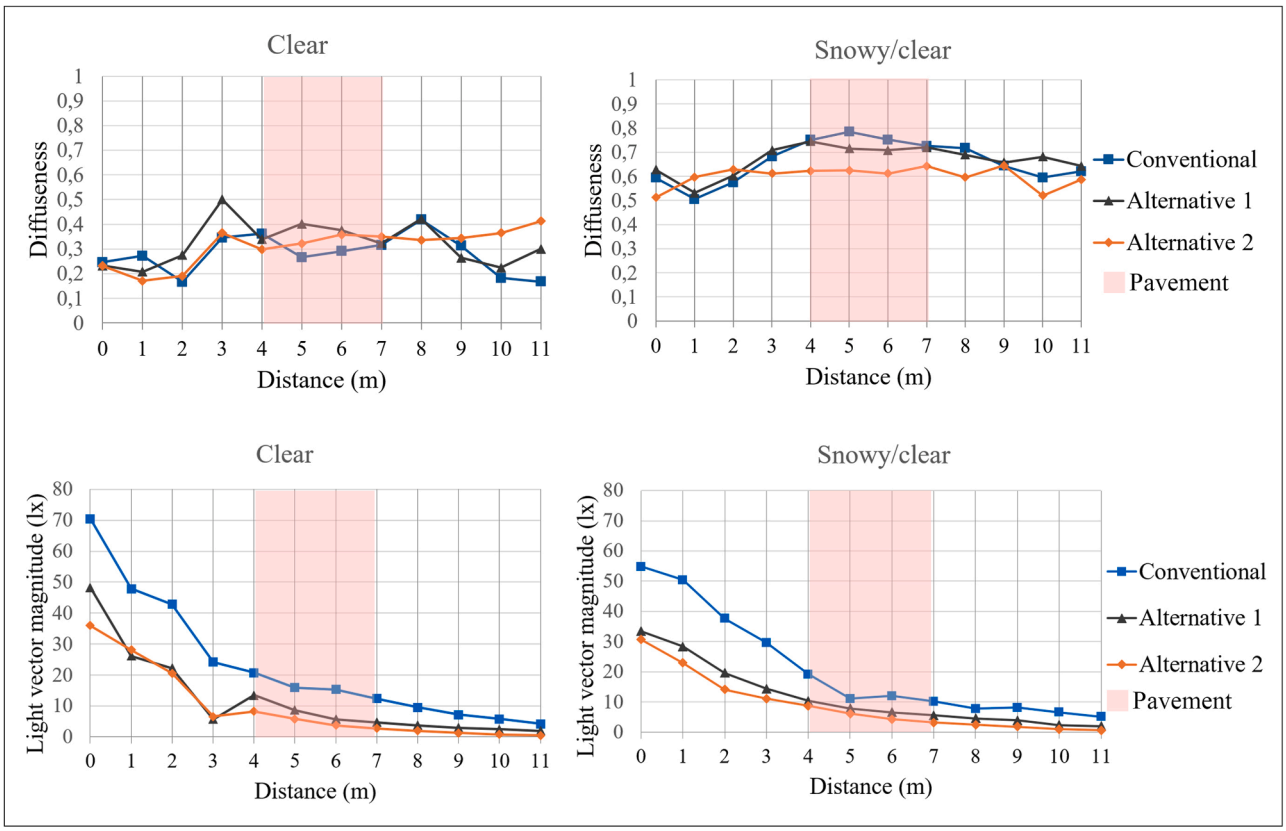


Fig. 11. Light vector magnitude and diffuseness for clear and snowy clear conditions and three luminaire configurations.

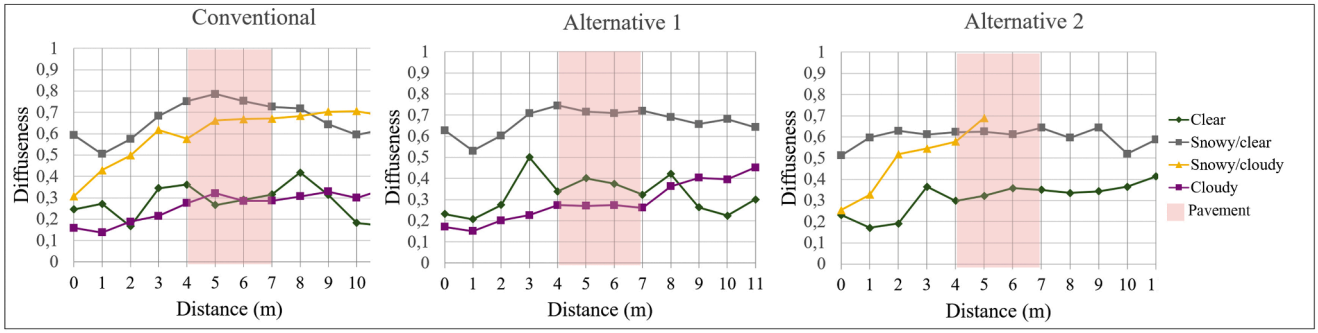


Fig. 12. Diffuseness as a function of distance under different conditions (clear, snowy clear, snowy cloudy, and cloudy) for three luminaire types: Conventional (left), Alternative 1 (middle), and Alternative 2 (right). The shaded pink area indicates the pavement region (distance 4–6).

particular, contrast metrics that rely on luminaire-to-background comparisons (e.g., Weber contrast) were found not to be robust. This was due to the high sensitivity of the luminance camera, at this distance the strong, luminance peaks were so small that they interfered with the camera's spatial resolution (pixel size).

To quantify the relative brightness of the luminaire's immediate surroundings relative to the background sky, we calculated the ratio L_{median} (reg. 1–3)/L_{median} (reg. 5). Here, L_{median} (reg. 1–3) was the median luminance of an area surrounding the luminaire (regions 1–3 with the 5th and 95th percentiles excluded), and L_{median} (reg. 5) was the median luminance of the sky region (region 5). Under non-snowy conditions, the Conventional luminaire system yielded the highest luminance ratios, with values up to 2.30 for Luminaire 1 and 1.61 and 1.54 for Luminaires 2 and 3, respectively. Under the same conditions, Alternative 1 showed lower ratios of 1.38, 1.11 and 1.13, and Alternative 2 yielded still lower values of 1.29, 1.09 and 1.05 for Luminaires 1–3, respectively. Under snowy conditions, the ratios for the Conventional system increased further, reaching 2.43, 2.64 and 2.45, whereas Alternative 2 maintained ratios of 0.94, 1.25 and 1.11, which were slightly lower than or comparable to those under non-snowy conditions. Taken together, these ratios indicate that the luminous environment around the Conventional luminaires, when normalised by sky luminance for each luminance map, stands out more clearly against the background sky than the environments around the Alternative luminaires, particularly the louvred alternative type. Fig. 14 shows the Michelson contrast of the luminance (based on the 5th and 95th percentiles) measured at region 6 for all the luminance maps obtained. This region included the road lane, luminaires, and the surrounding area. Under Clear conditions, the log-based Michelson contrast was highest for the Conventional luminaire (0.20), and decreased for Alternative 1 (0.15) and 2 (0.14). A similar pattern was observed under snowy conditions, although contrast values increased overall due to higher surface reflectance. The Conventional type reached a Michelson contrast of 0.37, whereas Alternative 2 reached 0.19. These results indicate a

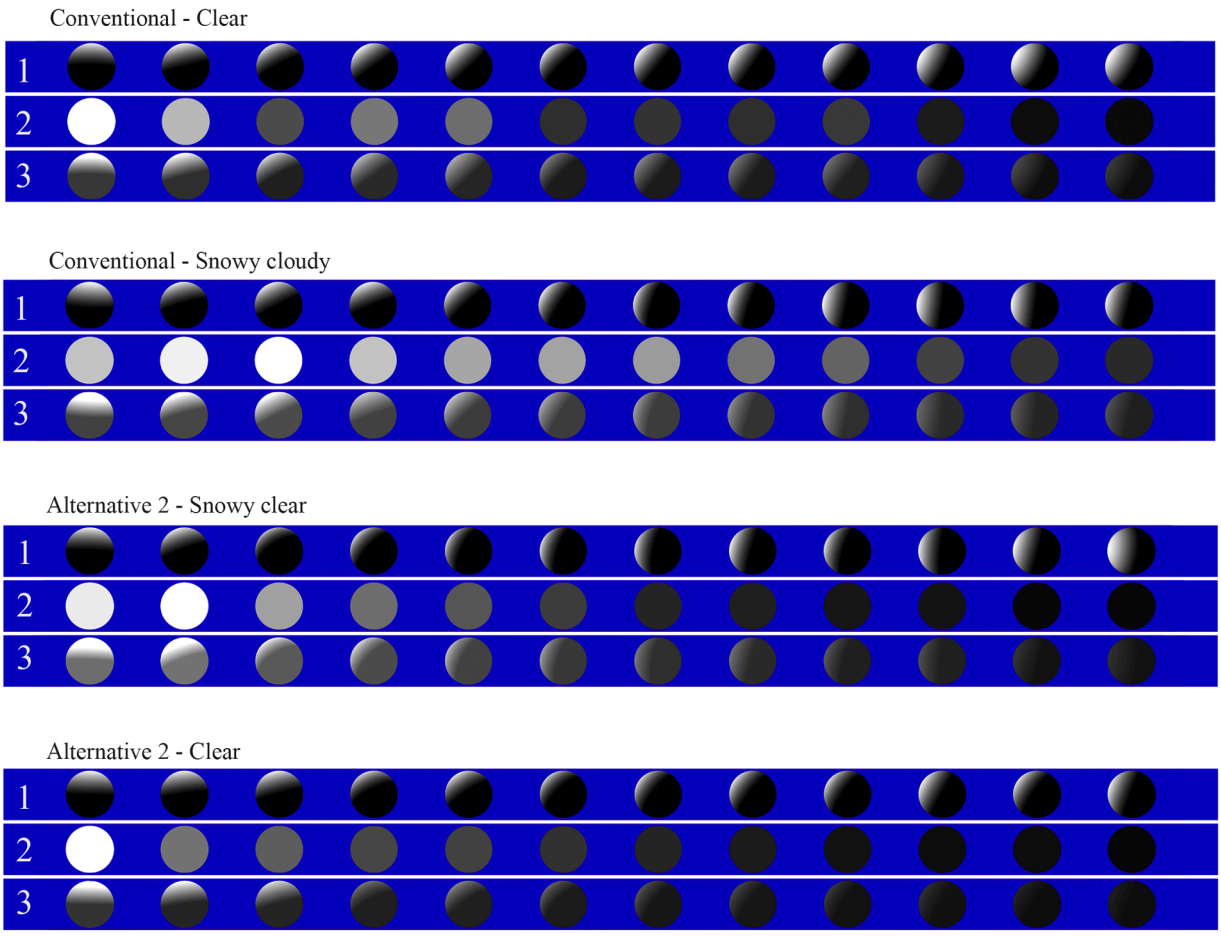


Fig. 13. Renderings of spheres based on the cubic measurements at the first 12 positions extending from beneath the luminaire (left) to 11 m into the transect (right) for four samples: Conventional clear, Conventional snowy cloudy, Alternative 2 snowy cloudy and Alternative 2 clear.

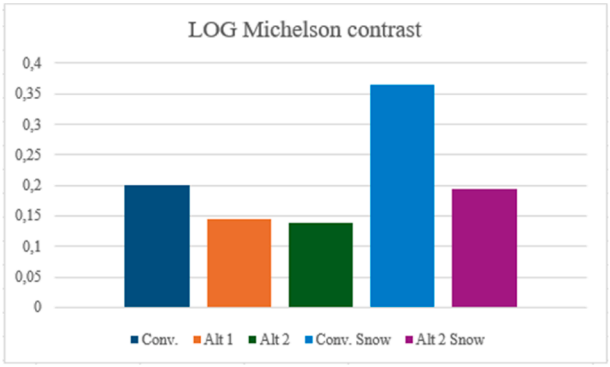


Fig. 14. The Michelson contrast, expressed on a logarithmic scale for each luminaire type.

systematically stronger luminance contrast for the Conventional luminaire configuration, particularly under snowy conditions.

5. Discussion

In this observational study, we measured and evaluated footpath lighting characteristics at varying distances from the luminaires as an indicator of potential light pollution, using horizontal and vertical illuminance in combination with luminance mapping and light-field measurements. Together, these methods captured complementary aspects of spill-light propagation into areas adjacent to the road. Kocifaj et al. note that spatial light distribution is typically tailored to site-specific requirements and that illuminance and luminance measurements are essential for outdoor lighting design [45]. This underscores the relevance of using photometric units also in light pollution management, instead of or in combination with radiometric units, as these metrics provide a standardised and widely used framework for evaluating and comparing lighting performance today. Future research should also include radiometric measurements to extend the analysis further to an eco-centric perspective.

As expected, both Alternative luminaires yielded lower horizontal illuminance and luminance than the Conventional luminaire, with additional reduction for the shielded configuration (Alternative 2), supporting that a louvre helps to reduce light spill and environmental impact. The horizontal illuminance measurements further demonstrated how the reflective properties of the surrounding environment affect illuminance levels. The horizontal illuminance measured for Conventional lighting increased by 116 % for Snowy clear compared to Clear. For Cloudy, it increased by 39 % and for the Snowy cloudy condition, by 350 %. These results align with Jechow and Hölker's [52] findings, where snow cover and clouds were found to increase zenith luminance levels by a factor of 188 for snow and clouds, and by a factor of 33 for snow alone. It also points to the increased impacts in snowy environments, where high albedo reflectance amplifies spill light [52,53]. These findings underscore the significant role that environmental factors play under real-world conditions, and the positive effect of reducing the illuminance levels in the side terrain, both by installing a louvre at the luminaire and reducing the luminous flux.

The effect of a full moon during one of the measurement nights

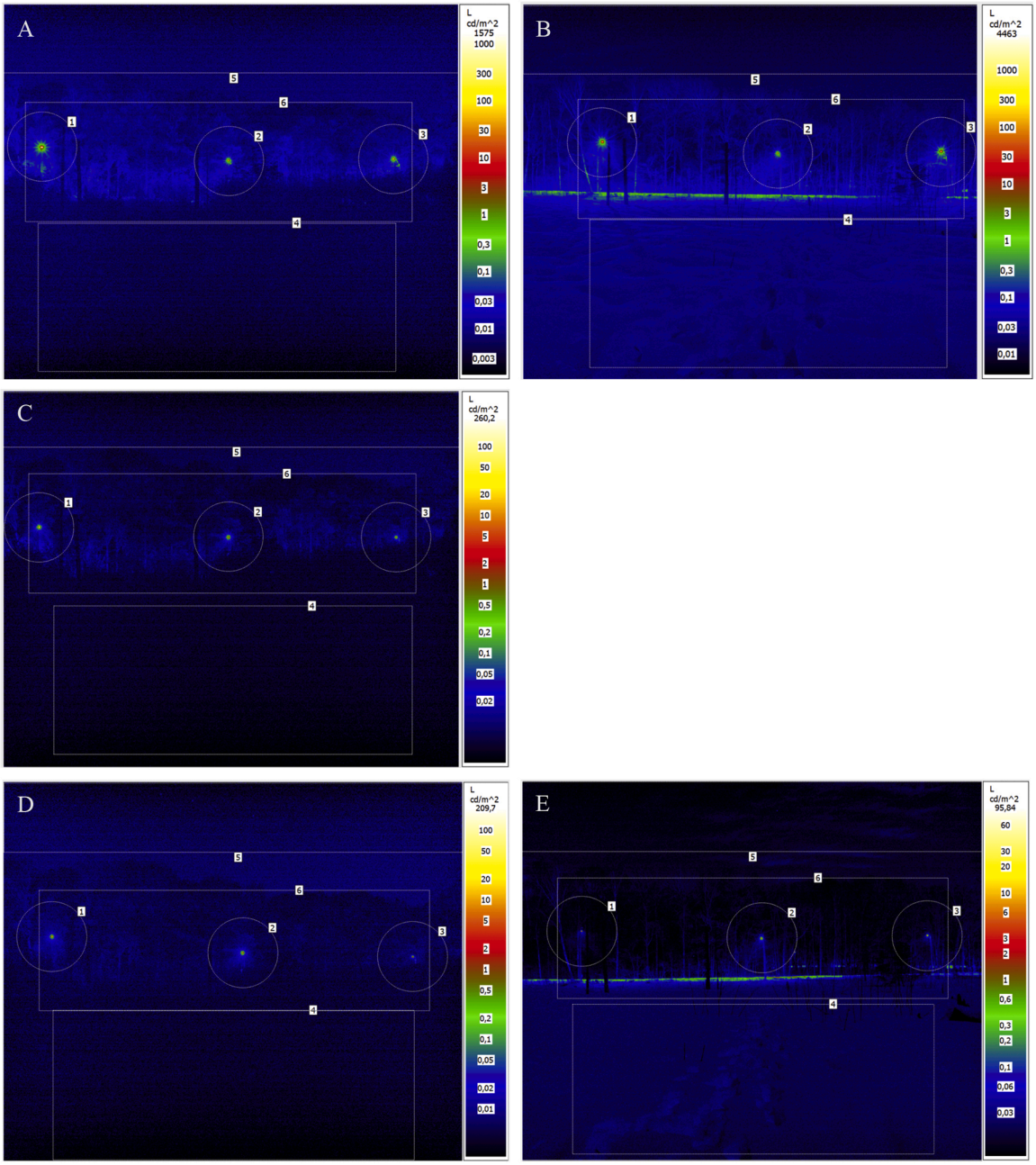


Fig. 15. Luminance maps for: A) Conventional luminaire, no snow; B) Conventional luminaire with snow; C) Alternative luminaire 1, no snow; D) Alternative 2, no snow; E) Alternative 2 with snow.

increased horizontal illuminance by 0.1 lx, consistent with Kyba et al. [54], who reported moonlight contributions of 0.05–0.1 lx depending on lunar elevation and atmospheric conditions. Such low light levels can influence natural systems, as shown by small nocturnal mammals that reduce foraging during bright full moons to avoid predation [32], underscoring the need to minimise artificial light even at low intensities. While studies in real-world conditions are influenced by varying factors, such as moonlight and varying atmospheric conditions, which complicate comparison, they reflect a natural variability in the environment. Future studies could attempt to isolate such incremental contributions by controlling for or modelling ambient illumination, which would help disentangle artificial and natural light effects. This could be done by installing control sensors for modelling effects over time. Cubic light measurements revealed the light qualities: density, vector magnitude, and diffuseness within the first 10 m of the transect, enabling objective assessment of the light field variation under different luminaires and reflective conditions. Over the pavement, managing light qualities is important for the appearance of other persons [55], particularly diffuseness, which affects modelling and contrasts [18]. In the measured transect, only slight differences in diffuseness were found among the three luminaire types, as it was highly affected by snow. This is a clear indication of the importance of considering the interplay between the luminaire lighting and the surrounding reflective conditions. Light vector magnitude decreased rapidly from directly beneath the luminaire to distances of approximately 3–4 m, coinciding with the edge of the pavement. The drop-off patterns were similar for the three luminaires, however the Conventional exhibited a higher light vector magnitude, between the two alternative luminaires, a slight drop was also seen for Alternative 2. Within the light field framework, the direction and intensity of the light vector characterise the dominant angular distribution

of luminous flux, enabling assessment of scattering. Our findings show that illumination from the luminaires was measurable up to 60 m, likely beyond. Further, the luminaires remained highly contrasted to the surroundings at 70 m

In the terrain, the applied louvre (Alternative 2) reduced vertical illuminance in the transect by 19,5 %, demonstrating its effectiveness. While reducing upward flux is a common strategy to mitigate light pollution, limiting spill light into the surrounding terrain is also critical for species on the ground. This calls for an implementation of a risk assessment framework to evaluate the impacts of ALAN in areas surrounding lighting installations. Such a framework would support a more informed assessment of ecological impacts and guide decision-making related to light pollution management.

These spatial patterns, the light flow is a concept coined by Lynes [56], worked out by Mury et al. and Kartashova et al. [19,49,57,58], where Mury et al. found that the light flow is related to the light vector and provides a quantitative description of light, and Kartashova et al. developed computational tools to visualise its volumetric properties and relationships to visual perception. The concept was extended with diffuseness by Xia [17,18]), highlighting how luminaire design shapes the light directionality and modelling effects, in combination with the surrounding surface scattering properties. Assessing the "light flow" through the environment can guide designers in minimising light intrusion into surrounding terrain within a spatial and directional analysis of the light *as and in* the field, as well as emphasising the role of luminaire design in light pollution management. It relates to Cuttle's "Third stage of the lighting profession", where he underpins the role of lighting design in moving toward balancing complex human needs as well as environmental sustainability [59]. Sphere renderings, as shown in Fig. 13, provide an effective tool for evaluating light qualities and the visual appearance of elements within illuminated environments – and how the lighting effects due to lighting and scattering penetrate the surroundings as "the effective flow of light", in terms of levels *and* directionality/diffuseness (which is relevant, e.g. for insects).

Please note that cubic measurements represent a spherical order first approach, which captures about 80–85 % of the probes' appearance, whereas Mury's plenopter can capture a second order approach (>90 %), meaning a close, but angular, low resolution approximation to the light field [12], in which higher-order "light textures" are averaged out. Still, this level of information is sufficient and can be rapidly measured for practical assessment and planning of lit environments. The sphere renderings shown in Fig. 13 also provide a visualisation of the "light flow" into the surroundings and can be valuable in design processes as tools for evaluating the spatial light distribution and supporting informed decisions about light qualities that can affect modelling and perception of faces, as well as the main direction and diffuseness of stray light. The light field [14] or plenoptic function [60] is a description of the light in a space, defining the luminance (L) as a function of the point in 3D space (x,y,z) for every angle (θ,ϕ), any wavelength (λ), and at any time (t) (*t*). It captures all possible views, in other words, all that is potentially to be seen. Since instantaneous capturing of the full 7D function is hard [21], practical applications use lower-dimensional subsets, e.g. a 5D version, ignoring time and wavelength, focusing on 3D space and 2D directions. Here, we used such a 5D version with a low angular resolution.

The luminance maps analyses showed that the conventional luminaire produced the highest luminance and contrast ratios in the resulting field of view, both when compared to the night sky and when Michelson contrast was calculated for an area around the road, including the luminaires. These high contrasts may attract insects [46], birds [28] and mammals [31], or conversely, may lead to avoidance behaviour in many species [29,30]. The luminaires studied in this experiment comply with EN 13,201 standard requirements for limiting high-angle light output ($\geq 90^{\circ}$ above the horizontal), helping to reduce potential obtrusive light. Despite this, our observations of the luminance maps indicate the presence of a very bright light source, visible at a significant distance. Recent research has demonstrated that bright concentrated light sources, such as streetlights or floodlights, can significantly impact the behaviour of insects [36] as well as create a barrier effect for mammals [61] and affect flight behaviour in birds [62]. In this study, the luminance maps were not deemed reliable for quantifying the absolute luminance of the luminaires. Across scenes, we observed inconsistencies that are most plausibly explained by luminous overflow and related imaging artefacts. As noted by Guha et al. [56], field luminance imaging is particularly sensitive to the material properties within the camera's field of view, and several systematic error sources are well documented, including lens vignetting, lens flare, luminous overflow/blooming, and mismatches between the camera sensor's spectral responsivity and the photopic V(λ) function [45]. In our case, field measurements with the luminance camera during the Norwegian winter were further complicated by low ambient temperatures, which likely affected the instrument's operational stability.

Our study results suggest that luminance mapping and light field measurements are valuable methods for assessing certain light pollution effects, as they enable the detection of the effective flow of light into the terrain. They provide valuable data complementary to horizontal and vertical illuminance measurements and to the methods already commonly used by lighting designers and engineers [41]. The impacts of ALAN on ecosystems are diverse, and it is challenging to find a single mitigation strategy that addresses all species [63]. Thus, coordinated efforts to reduce artificial light are essential, including reduced intensities, duration, and spectral composition. Light distribution study and management are essential parts of eco-centric lighting approaches.

Our results may not fully capture the ecological dimensions, as radiometric measurements were not conducted, and the primary aim of this study was to explore methods that are easy for lighting designers and engineers to adopt. Additional analysis is necessary to align with biological sciences. Further, the study was carried out along a single transect, further research on multiple transects with different orientations, lengths, and positions between luminaires is required to fully understand the spatial variability of footpath lighting. Measurements were taken under real-world Nordic conditions, where snow cover, clouds, and low temperatures affected both environmental reflectance and instrument performance. This provides ecological validity, however, it also introduces confounding factors related to natural dynamics in nature and may limit the generalisability to different climatic regions. To minimise interference from external light sources, the measurements were conducted in a semi-rural setting. However, this context may limit the applicability of the findings to more urban contexts. Furthermore, the study did not include benchmarking against conventional discharge lamp technologies, restricting direct comparison with such lighting systems. Within the limited scope of this research, we show a novel integrated way of combining methodologies for a holistic assessment of outdoor lighting.

6. Conclusion

Road luminaires are designed to illuminate roads and improve visibility, but inevitably scatter and reflect light into adjacent areas. This study shows that when luminaire configurations are aimed at reducing light pollution, such as the two alternative luminaire types tested, they can substantially reduce stray light into adjacent terrain. However, it often entails reduced illumination on the footpath, calling for attention to the distribution of light on the footpath. In our previous study, it was found that the Alternative luminaire positively influenced face evaluations, despite lower illuminance levels [64]. These trade-offs need to be evaluated explicitly, both in terms of human visual performance and ecological responsibility. Introducing a luminaire with a louvre reduced the spill light in the terrain, suggesting that shielded optics can mitigate environmental impact.

Our findings also demonstrate the value of combining multiple measurement approaches. Horizontal illuminance was a simple way of revealing the gradual decrease in illumination and clearly demonstrated

differences between environmental conditions. Cubic light measurements provided complementary information on light quality, such as light vector direction, density and diffuseness, particularly of interest in the area over the footpath, but also point to the propagation of the light, the so-called effective light flow into the terrain. Luminance maps further complemented these methods by characterising the appearance of bright point light sources at a substantial viewing distance (70 m in our case), allowing us to assess high-contrast regions that may be critical for visual perception, and potential ecological impacts.

The strong influence of snow cover and cloud conditions on measured light levels underlines that outdoor lighting performance should, as far as possible, be verified in the specific environmental context in which a system operates. Standard metrics, such as horizontal illuminance, while useful, are insufficient on their own and poorly capture visual experience and spatial and directional qualities of light. Luminance mapping and light field analysis provide a more informative description of how light is distributed and perceived, and these approaches can be further combined with radiometric measurements that are ecologically relevant for specific species.

For the practical implementation of this ecocentric framework, we suggest cubic illuminance measurements in the immediate vicinity of and between the luminaires. This enables characterising the three-dimensional light distribution for human users. This approach enables better assessment of lighting conditions for pedestrians, as outlined in our previous work [64]. To evaluate the reach of light propagation, we recommend conducting both horizontal and vertical illuminance and irradiance measurements in the terrain. Luminance or radiance camera measurements are suggested to assess the light distribution and the distant contrast effects of the lighting installation. Future research should aim to establish threshold values for the measurement parameters, translating the ecocentric framework into operational design guidelines and policy recommendations. Spectral extensions beyond the human range, and knowledge regarding spectral sensitivities of different (plant and animal) species, will in the long term be needed for a comprehensive eco-centric approach.

The study presented an exploratory study of a novel approach to assessing light trespass in eco-centric contexts, introducing the concepts of the “eco-centric light field”, and emphasising the management of what Mury et al. [58] called the light flow. An ecocentric approach to lighting analysis recognises that outdoor illumination must balance human visibility needs with the ecological need for natural darkness. It entails assessing not only how light benefits people but also how it spreads and therefore affects the surrounding environment. By integrating horizontal illuminance, light-field measurements and luminance imaging, designers and researchers can obtain a more comprehensive understanding of how luminaires shape both the immediate visual environment and distant, sky-referenced contrasts, thereby enabling more robust, light-pollution-aware design and evaluation of outdoor lighting systems.

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CRediT authorship contribution statement

Helga Iselin Wåseth: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Veronika Zaikina:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Sylvia Pont:** Writing – review & editing, Visualization, Supervision, Software, Methodology, Formal analysis, Conceptualization.

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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Data availability

Data will be made available on request.

References

[1] P.R. Boyce, The benefits of light at night, Build. Environ. 151 (2019) 356–367, https://doi.org/10.1016/j.buildenv.2019.01.020.
[2] F. Falchi, P. Cinzano, C.D. Elvidge, D.M. Keith, A. Haim, Limiting the impact of light pollution on human health, environment and stellar visibility, J. Environ. Manag. 92 (2011) 2714–2722, https://doi.org/10.1016/j.jenvman.2011.06.029.
[3] C.C.M. Kyba, T. Kuester, M.A.S. de, K. Baugh, A. Jechow, F. Hölker, et al., Artificially lit surface of earth at night increasing in radiance and extent, Sci. Adv. 3 (2017) e1701528, https://doi.org/10.1126/sciadv.1701528.
[4] M.A Sanchez de, J. Bennie, E. Rosenfeld, S. Dzurjak, K. Gaston, Environmental risks from artificial nighttime lighting widespread and increasing across Europe, Sci. Adv. 8 (2022) 6891, https://doi.org/10.1126/sciadv.abl6891.
[5] T. Longcore, C. Rich, Ecological light pollution, Front. Ecol. Environ. 2 (2004) 191–198, https://doi.org/10.1890/1540-9295(2004)002%5B0191:ELP%5D2.0.CO;2.
[6] A. Jägerbrand, K. Spoelstra, Effects of anthropogenic light on species and ecosystems, Science 380 (2023) 1125–1130, https://doi.org/10.1126/science.adg3173.
[7] D. Sanders, E. Frago, R. Kehoe, C. Patterson, K.J. Gaston, A meta-analysis of biological impacts of artificial light at night, Nat. Ecol. Evol. (2020) 1–8, https://doi.org/10.1038/s41559-020-01322-x.
[8] K.J. Gaston, M.A.S. de, Environmental impacts of artificial light at night, Annu. Rev. Environ. Resour. 47 (2022) 373–398, https://doi.org/10.1146/annurev-environ-112420-014438.
[9] A. Jägerbrand, C. Bouroussis, Ecological impact of artificial light at night: effective strategies and measures to deal with protected species and habitats, Sustainability 13 (2021) 5991, https://doi.org/10.3390/su13115991.
[10] J. Brons, J. Bullough, M. Rea, Outdoor site-lighting performance: a comprehensive and quantitative framework for assessing light pollution, Light Res. Technol. 40 (2008) 201–224, https://doi.org/10.1177/1477153508094059.
[11] T. Edensor, The gloomy city: rethinking the relationship between light and dark, Urban Stud. 52 (2015) 422–438, https://doi.org/10.1177/0042098013504009.
[12] P.S.C. Light, Toward a transdisciplinary science of appearance and atmosphere, Annu. Rev. Vis. Sci. 5 (2019) 503–527, https://doi.org/10.1146/annurev-vision-091718-014934.
[13] D.E. Nilsson, J. Smolka, Quantifying biologically essential aspects of environmental light, J. R. Soc. Interface. 18 (2021) 20210184, https://doi.org/10.1098/rsif.2021.0184.
[14] A. Gershun, The light field. Vol. 18. 1st–4th ed, J. Math. Phys. (1939).
[15] C. Cuttle, Lighting Design - A Perception Based Approach, 1st ed., Routledge, 2015.
[16] C. Cuttle, Research note: a practical approach to cubic illuminance measurement, Light Res. Technol. 46 (2014) 31–34, https://doi.org/10.1177/1477153513498251.
[17] L. Xia, S. Pont, I. Heynderickx, Light diffuseness metric, part 2: describing, measuring and visualising the light flow and diffuseness in three-dimensional spaces, Light Res. Technol. 49 (2017) 428–445, https://doi.org/10.1177/1477153516631392.
[18] L. Xia, S. Pont, I. Heynderickx, Light diffuseness metric part 1: theory, Light Res. Technol. 49 (2017) 411–427, https://doi.org/10.1177/1477153516631391.
[19] T. Kartashova, Structures of physical and visual light fields: measurement, Comp. Vis. (2018), https://doi.org/10.4233/uuid:fd7e7b74-5719-49f5-856a-a5ee3784c2ea.
[20] S.C. Pont, Spatial and Form-Giving Qualities of light. Handbook of Experimental Phenomenology: Visual Perception of Shape, Space and Appearance, Wiley-Blackwell, West-Sussex, UK, 2013, pp. 205–222.
[21] C. Yu, M. Wijntjes, E. Eisemann, S. Pont, Quantifying the spatial, temporal, angular and spectral structure of effective daylight in perceptually meaningful ways, Opt. Express. OE. 31 (2023) 8953–8974, https://doi.org/10.1364/OE.479715.
[22] C. Yu, E. Eisemann, S. Pont, Effects of inter-reflections on the chromatic structure of the light field, Light Res. Technol. 55 (2023) 218–236, https://doi.org/10.1177/14771535211058202.
[23] Y. Morgenstern, W.S. Geisler, R.F. Murray, Human vision is attuned to the diffuseness of natural light, J. Vis. 14 (2014) 15, https://doi.org/10.1167/14.9.15.

[24] K.J. Gaston, J.P. Duffy, S. Gaston, J. Bennie, T.W. Davies, Human alteration of natural light cycles: causes and ecological consequences, Oecologia 176 (2014) 917–931, https://doi.org/10.1007/s00442-014-3088-2.
[25] G. Kalinkat, M. Grubisic, A. Jechow, R.H.A. van Grunsven, S. Schroer, F. Hölker, Assessing long-term effects of artificial light at night on insects: what is missing and how to get there, Insect Conserv. Divers. 14 (2021) 260–270, https://doi.org/10.1111/icad.12482.
[26] A.C.S. Owens, P. Cochard, J. Durrant, B. Farnworth, E.K. Perkin, B. Seymoure, Light pollution is a driver of insect declines, Biol. Conserv. 241 (2020) 108259, https://doi.org/10.1016/j.biocon.2019.108259.
[27] F. Hölker, C. Wolter, E.K. Perkin, K. Tockner, Light pollution as a biodiversity threat, Trends Ecol. Evol. 25 (2010) 681–682, https://doi.org/10.1016/j.tree.2010.09.007.
[28] C.A. Adams, E. Fernández-Juricic, E.M. Bayne, C.C St Clair, Effects of artificial light on bird movement and distribution: a systematic map, Environ. Evid. 10 (2021) 37, https://doi.org/10.1186/s13750-021-00246-8.
[29] M. Ciach, A. Fröhlich, Habitat type, food resources, noise and light pollution explain the species composition, abundance and stability of a winter bird assemblage in an urban environment, Urban Ecosyst. 20 (2017) 547–559, https://doi.org/10.1007/s11252-016-0613-6.
[30] A.C.S. Owens, S.M. Lewis, The impact of artificial light at night on nocturnal insects: a review and synthesis, Ecol. Evol. 8 (2018) 11337–11358, https://doi.org/10.1002/ece3.4557.
[31] C.L. Seewagen, J. Nadeau-Gneckow, A.M. Adams, Far-reaching displacement effects of artificial light at night in a north American bat community, Glob. Ecol. Conserv. 48 (2023) e02729, https://doi.org/10.1016/j.gecco.2023.e02729.
[32] J. Hoffmann, R. Palme, J.A. Eccard, Long-term dim light during nighttime changes activity patterns and space use in experimental small mammal populations, Environ. Pollut. 238 (2018) 844–851, https://doi.org/10.1016/j.envpol.2018.03.107.
[33] D.M. Shier, A.K. Bird, T.B. Wang, Effects of artificial light at night on the foraging behavior of an endangered nocturnal mammal, Environ. Pollut. 263 (2020) 114566, https://doi.org/10.1016/j.envpol.2020.114566.
[34] van Grunsven R.H.A., Creemers R., Joosten K., Donners M., Veenendaal E.M. Behaviour of migrating toads under artificial lights differs from other phases of their life cycle 2017. https://doi.org/10.1163/15685381-00003081.
[35] C.J. Macgregor, M.J.O. Pocock, R. Fox, D.M. Evans, Effects of street lighting technologies on the success and quality of pollination in a nocturnally pollinated plant, Ecosphere 10 (2019) e02550, https://doi.org/10.1002/ecs2.2550.
[36] S.T. Fabian, Y. Sondhi, P.E. Allen, J.C. Theobald, H.T. Lin, Why flying insects gather at artificial light, Nat. Commun. 15 (2024) 689, https://doi.org/10.1038/s41467-024-44785-3.
[37] T. Degen, O. Mitesser, E.K. Perkin, N.S. Weiß, M. Oehlert, E. Mattig, et al., Street lighting: sex-independent impacts on moth movement, J. Anim. Ecol. 85 (2016) 1352–1360, https://doi.org/10.1111/1365-2656.12540.
[38] K.G. Horton, J.J. Buler, S.J. Anderson, C.S. Burt, A.C. Collins, A.M. Dokter, et al., Artificial light at night is a top predictor of bird migration stopover density, Nat. Commun. 14 (2023) 7446, https://doi.org/10.1038/s41467-023-43046-z.
[39] M.F. Land, Animal Eyes, 2nd ed., Oxford University Press, Oxford, New York, NY, 2012.
[40] V. Vasas, M.C. Lowell, J. Villa, Q.D. Jamison, A.G. Siegle, P.K.R. Katta, et al., Recording animal-view videos of the natural world using a novel camera system and software package, PLoS Biol. 22 (2024) e3002444, https://doi.org/10.1371/journal.pbio.3002444.
[41] A. Follestad, NINA-rapport 1081 Effekter av Kunstig Nattbelysning På Naturmangfoldet -en litteraturstudie, NINA - Norsk institutt for naturforskning, 2014.
[42] CEN. EN 13201-2:2016 – road lighting – part 2: performance requirements 2016.
[43] D. Sanders, E. Frago, R. Kehoe, C. Patterson, K.J. Gaston, A meta-analysis of biological impacts of artificial light at night, Nat. Ecol. Evol. (2020) 1–8, https://doi.org/10.1038/s41559-020-01322-x.
[44] H. Spoelstra, New device for monitoring the colors of the night, J. Quant. Spectrosc. Radiat. Transf. 139 (2014) 82–89, https://doi.org/10.1016/j.jqsrt.2014.01.001.
[45] M. Kocifaj, S. Wallner, J.C. Barentine, Measuring and monitoring light pollution: current approaches and challenges, Science 380 (2023) 1121–1124, https://doi.org/10.1126/science.adg0473.
[46] M. Dietenberger, A. Jechow, G. Kalinkat, S. Schroer, B. Saathoff, F. Hölker, Reducing the fatal attraction of nocturnal insects using tailored and shielded road lights, Commun. Biol. 7 (2024) 671, https://doi.org/10.1038/s42003-024-06304-4.
[47] M. Viikari, A. Ekrias, M. Eloholma, L. Halonen, Modeling spectral sensitivity at low light levels based on mesopic visual performance, Clin. Ophthalmol. 2 (2008) 173–185, https://doi.org/10.2147/opth.s2414.
[48] F. Falchi, P. Cinzano, D. Duriscoe, C.C.M. Kyba, C.D. Elvidge, K. Baugh, et al., The new world atlas of artificial night sky brightness, Sci. Adv. 2 (2016) e1600377, https://doi.org/10.1126/sciadv.1600377.
[49] T. Kartashova, S. Te Pas, H. Ridder, S. Pont, Light shapes: perception-based visualizations of the global light transport, ACM Trans. Appl. Percept. 16 (2019) 1–17, https://doi.org/10.1145/3232851.
[50] T. Kartashova, H. de Ridder, S. te Pas, S. Pont, A toolbox for volumetric visualization of light properties, Light Res. Technol. 51 (2019) 838–857, https://doi.org/10.1177/1477153518822159.
[51] S. Safranek, R.G. Davis, Sources of error in HDRI for luminance measurement: a review of the literature, LEUKOs 17 (2021) 187–208, https://doi.org/10.1080/15502724.2020.1721018.
[52] A. Jechow, F. Hölker, Snowglow-the amplification of skyglow by snow and clouds can exceed full moon illuminance in suburban areas, J. Imaging. 5 (2019) 69, https://doi.org/10.3390/jimaging5080069.
[53] F. Zhang, N. Wang, L. Zhang, Y. Chu, S. Wang, Y. Huang, Effects of snow cover on urban light climate environment in the high latitudes of northeast China, Sci. Rep. 13 (2023) 1–16, https://doi.org/10.1038/s41598-023-35825-x.
[54] C.C.M. Kyba, A. Mohar, T. Posch, How bright is moonlight? AG 58 (2017) 1.31–1.32, https://doi.org/10.1093/astrogeo/atx025.
[55] H.I. Wåseth, V. Zaikina, S.C. Pont, Footpath lighting: optical, visual and perceptual characteristics of the social light field, Accept. Publ. LEUKOS (2025).
[56] J.A. Lynes, Principles of Natural Lighting, Elsevier Pub. Co., Amsterdam, 1968.
[57] A.A. Mury, S.C. Pont, J.J. Koenderink, Analysis of second order light fields in closed 3D spaces. Frontiers in Optics 2008, Optica Publishing Group, Rochester, New York United States, 2008, p. FMC3, https://doi.org/10.1364/FIO.2008.FMC3.
[58] A.A. Mury, S.C. Pont, J.J. Koenderink, Representing the light field in finite three-dimensional spaces from sparse discrete samples, Appl. Opt. AO. 48 (2009) 450–457, https://doi.org/10.1364/AO.48.000450.
[59] F. Mahlab, H. Yamaguchi, Y. Shimozima, N. Yoshizawa, H. Cai, A joint validation study on camera-aided illuminance measurement, Light Res. Technol. 55 (2023) 571–593, https://doi.org/10.1177/14771535231154169.
[60] E.H. Adelson, J.R. Bergen, The plenoptic function and the elements of early vision, in: M. Landy, J.A. Movshon (Eds.), Computational Models of Visual Processing, The MIT Press, 1991, https://doi.org/10.7551/mitpress/2002.003.0004.
[61] R. Sordello, D.Y. Ouédraogo, C. Chassoulier, S. Aulagnier, A. Coulon, Y. Reyjol, Does artificial light interfere with the activity of nocturnal mammals? An experimental study using road underpasses, Biol. Conserv. 302 (2025) 110960, https://doi.org/10.1016/j.biocon.2024.110960.
[62] S.A. Cabrera-Cruz, R.P. Larkin, M.E. Gimpel, J.G. Gruber, Z.T.J. Jr, J.J Buler, Potential effect of low-rise, downcast artificial lights on nocturnally migrating land birds, Integr. Comp. Biol. 61 (2021) 1216–1236, https://doi.org/10.1093/icb/icab154.
[63] J. Falcón, A. Torriglia, D. Attia, F. Viénot, C. Gronfier, F. Behar-Cohen, et al., Exposure to artificial light at night and the consequences for flora, fauna, and ecosystems, Front. Neurosci. 14 (2020), https://doi.org/10.3389/fnins.2020.602796.
[64] H.I. Wåseth, V. Zaikina, S. Pont, The social light field in eco-centric outdoor lighting, Buildings 15 (2025) 3052, https://doi.org/10.3390/buildings15173052.