ORIGINAL ARTICLE

Polarised light pollution on river water surfaces caused by artificial light at night from illuminated bridges and surroundings

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ABSTRACT

Artificial light at night originating from bridge illumination can cause polarised light pollution when it is reflected at water body surfaces. This alters the optical conditions of a river at night and potentially interferes with natural polarisation signals from for example moonlight. Therefore, this type of light pollution could detrimentally change the behaviour of organisms sensitive to polarised light, a navigational cue and signal known to be used *e.g.* by flying water-seeking insects to detect suitable aquatic habitats to reproduce and lay eggs. So far, polarised light pollution from artificial light at night is understudied. Here, we quantify polarised light pollution at the water's surface near seven illuminated bridges crossing the river Spree in Berlin. Our measurements show for the first time, that nocturnal bridge illumination induces polarised light pollution towards potential flying paths of polarotactic aquatic insects. On average, around 9% of the water surfaces at the investigated bridges were highly polluted by polarised light, with values ranging between 3 and 12 % for each bridge. Thus, polarised light pollution from artificial light at night is an emergent pollutant for aquatic systems. Future work on this topic should include more comprehensive measurements, further ecological studies on its impacts and the development of sustainable lighting solutions that can contribute to the protection of riverine nightscapes.

INTRODUCTION

Light is the part of the electromagnetic spectrum visible to the human eye, and such electromagnetic waves can be polarised (Foster *et al.*, 2018) (Supplementary Material). Generally, humans are not able to perceive polarised light, apart from some very specific situations (Haidinger, 1844), while several animals are able to perceive it (Foster *et al.*, 2018). Polarisation can occur when unpolarised light is reflected or transmitted at surfaces that have a specific polarisation direction or by scattering within a medium (the atmosphere or water) (Fig. S2) (Foster *et al.*, 2018). Water surfaces in nature are a typical example where light is reflected so that the resulting reflected light is (at least partly) linearly polarised. As other surfaces might not reflect the light of a specific polarisation like water, the polarisation information can be understood as encoded optical information about the surroundings (*e.g*., water or the absence of water), and it can change how surfaces and objects are perceived by organisms that can detect them (Foster *et al*., 2018).

In nature, polarisation is a well-known light property that is often found in scattered skylights, the reflected light of the surface from waterbodies, rocks, soil, and vegetation (Shashar *et al*., 1995; Wehner, 2001; Cronin, 2018). Polarised light has been shown to be used by vertebrates and invertebrates as an optical source of encoded information about habitats and surroundings (*e.g*., as a celestial compass and aquatic habitat information). For instance, fish, birds, and invertebrates such as insects use polarised light to locate habitats (Brines and Gould, 1982; Nilsson and Warrant, 1999; Muheim, 2011; Goldsmith, 1975; Bernáth *et al*., 2001; Labhart, 1988). Bees, ants, and arthropods make use of polarised light as a navigational cue to locate the sun's position (*via* polarised light in the sky) and as a reference to return to nesting sites (Wehner, 1989). Flying aquatic insects detect waterbodies through the polarised reflection of light at the water's surface (Schwind, 1991). Under natural light conditions, waterbodies are known to reflect horizontally polarised light and have been shown to guide so-called polarotactic organisms, whose visual systems can detect polarised light (Horváth *et al*., 2009; Schwind, 1989), which makes polarisation an advantage that facilitates navigation and habitat selection (Wehner, 2001; Cronin, 2018; Muheim, 2011; Bernáth *et al*., 2001; Horváth *et al*., 2009). Fig. 1 shows a typical scenario in which the polarisation of reflected moonlight is expected to be used as a signal that aids mayflies during their flights to detect the water's surface.

Artificial light at night (ALAN) incident on inland waters (*i.e*., surfaces where ALAN is not intended to be) will create polarised light signals when reflected. This will potentially cause ALAN-induced polarised light pollution (PLP) at the water surface that can eventually turn illuminated waters and surfaces into an ecological trap at night (Haynes and Robertson, 2021; Szás *et al*., 2015). Consequently, PLP can potentially affect the behaviour of flying nocturnal species sensitive to polarised light (Horváth *et al*., 2009; Owens *et al*., 2020; Egrí *et al*., 2019). As ALAN is a global problem that continues to increase in radiance and extent (Falchi *et al*., 2016; Kyba *et al*., 2017), concerns

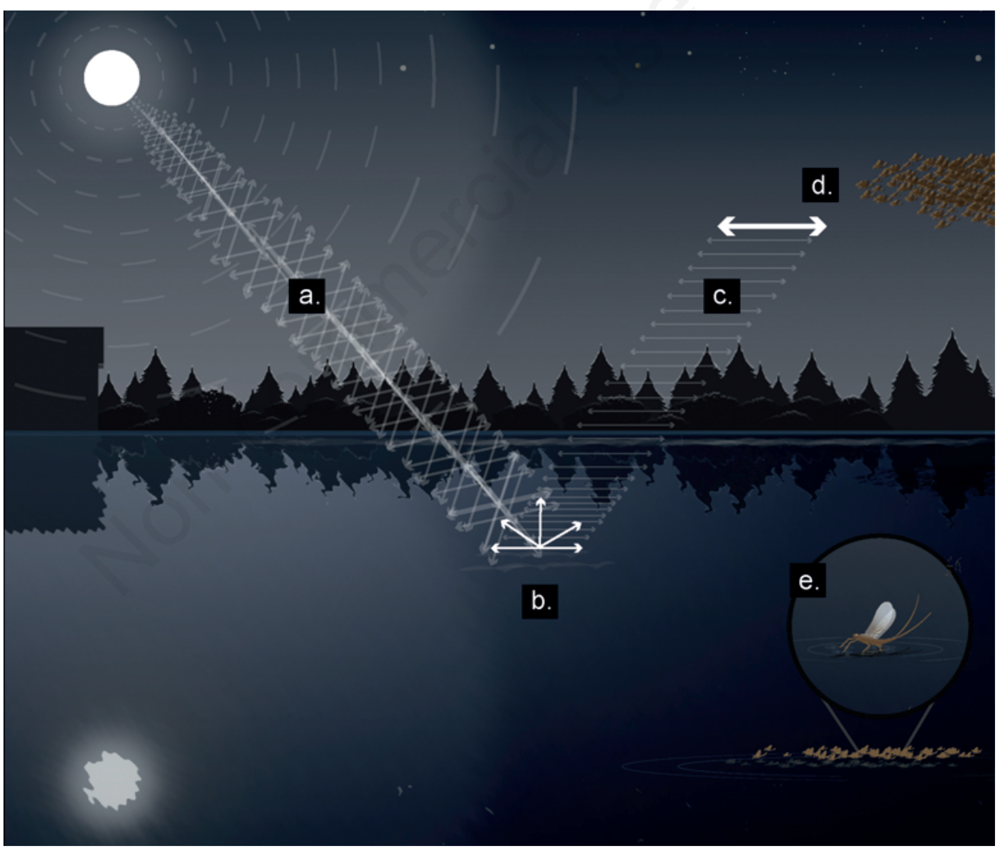

Fig. 1. Sketch of a river at night that is naturally illuminated by a full moon. Here, polarisation signals from moonlight reflected at the water's surface serve as a navigational cue for reproductive behaviour. In natural conditions, moonlight is a distant single source that can also be used for navigation due to its large contrast within the relatively dark surroundings. At the same time, its position remains nearly constant within the sky for animals navigating on typical spatial scales (i.e., where the position of the moon in the sky remains almost fixed). During a full moon and a cloudless night, **(a)** unpolarised incident moonlight strikes **(b)** the boundary of air and water where mainly horizontally polarised light is reflected. The reflected linear polarised light becomes a source of optical information to locate the water surface and a reference for orientation and navigation used by **(d)** polarotactic-flying organisms, such as mayflies. The moon's reflected polarised light is often related to foraging and reproductive behaviours in nocturnal flying aquatic insects (Brines and Gould, 1982). Horizontally reflected polarised moonlight serves as optical information that indicates a potential habitat for mating or laying eggs (e). Source: authors' own work.

about PLP are also growing (Horváth *et al*., 2009; Egrí *et al.*, 2019). ALAN directly incident on land or water can be up to 1,000 times brighter than a natural full moon (Jechow and Hölker, 2019), and ALAN that scatters in the atmosphere as skyglow can also outshine moonlight (Jechow *et al*., 2020). Thus, a substantial amount of ALAN can reach polarising surfaces and induce maladaptive behaviours or physiological responses (Longcore and Rich, 2004; Hölker *et al*., 2021).

One study on the distinct polarisation properties of a dark lake suggests that PLP can influence the detectability of the water, which could potentially affect the behaviour of polarotactic insects (Szás *et al*., 2023; Fraleigh *et al*., 2021). Another study demonstrated that polarised ALAN and unpolarised ALAN at bridge surfaces attracts and traps mayflies (Szás *et al*., 2015; Turcsányi *et al*., 2009). This combination of unpolarised and polarised ALAN will likely contribute to the increased attraction of nocturnal flying species towards bridge structure, which can veil a bridge into an ecological trap (Fraleigh *et al*., 2021; Black and Robertson, 2020; Robertson and Chalfoun, 2016). In mayflies, polarised ALAN at bridges has been shown to affect their natural behaviour and swarming dynamics (Egrí *et al.*, 2019).

Studies on polarisation signals have demonstrated that man-made surfaces, including asphalt roads (Kriska *et al*., 1998), solar panels (Black and Robertson, 2020), black and grey horizontal reflectors (Malik *et al*., 2008), black and white cloth (Horváth *et al*., 2011), cars (Wildermuth and Horvéth, 2005; Kriska *et al*., 2006), and dark glass surfaces (Malik *et al*., 2008; Kriska *et al*., 2008) when illuminated with natural light (sunlight), have polarising properties comparable to those of water surfaces when illuminated (Horváth *et al*., 2014) and have demonstrated reflected horizontally polarised light likely to turn these surfaces into ecological traps for attracted polarotactic organisms. We have recently raised the issue of ALAN from illuminated bridges in inland waters (Pérez Vega *et al*., 2024) and also mentioned the problem of PLP from ALAN in a review paper (Hölker *et al*., 2023). However, so far, no studies have considered PLP from ALAN being reflected at the water's surface. Most work was done on ALAN creating PLP on non-water surfaces mimicking the impression of water surfaces, and few studies have done that in the context of illuminated bridges (Szás *et al*., 2015; Egrí *et al.*, 2019). PLP induced by bridge illumination remains a multi-faceted research question. Thus, measuring how ALAN is polarised is a crucial first step in our understanding of the vision of different animal groups, habitat selection (Schwind, 1983), and ecological interactions of organisms with their environment.

Only a few studies have addressed the potential impact of ALAN on the river Spree in Berlin and its inhabiting species. Perkin *et al.* (2014) demonstrated in the river Spree south-east of Berlin that the proportion of aquatic insects (compared to terrestrial) in traps at 0, 3 and 40 m from streetlights along the shoreline was higher when they were switched on than when they were switched off. This suggests that adult aquatic insects may be more susceptible to the effects of light pollution than terrestrial insects. Furthermore, the illumination of bridges and adjacent areas has been shown to induce different types of potential underwater light barriers with unnatural light variations (Pérez Vega *et al.*, 2024). Since aquatic insects spend most of their life cycle as larvae or nymphs in water and then stay near these aquatic systems as adults, the question arises whether ALAN can induce nocturnal polarisation patterns that can lead to disturbance of flying aquatic insects, many of which are polarotactic. In this study, we i) quantify the reflection polarisation patterns of ALAN from illuminated bridges crossing a river and at potential flying path positions of polarotactic aquatic insects to ii) draw up potential implications for water-seeking insects. Furthermore, we iii) identify the different sources of reflected polarised light in/near illuminated bridges to estimate the extent to which bridge ALAN becomes horizontally polarised by reflection at the water's surface.

METHODS

Location of observation

The night-time measurements were performed during clear sky conditions on the 24th of March 2022, in Berlin, Germany. Measurements were obtained between ca.18:30 and 23:30 local time (GMT +1), with the moon setting at approximately 20:45 (GMT +1). The measurement area covers a 10 km route from West to East (Fig. 2a), which includes seven illuminated bridges crossing the river Spree in Berlin. Prior to the measurement night, the seven illuminated bridges were scouted by foot to determine one position at each bridge to obtain measurements considering potential insect flying perspectives over the river (see Tab. S1 for more information on the position at which measurements were taken at each measurement site). Once the position at each bridge was set, a mapped route was established to perform one-night ground measurements over seven illuminated bridges. The measurements were used to determine if PLP occurred at illuminated bridges. The measurements do not cover all possible positions an insect might consider when flying over a river.

Applied technical instruments

A digital single-lens reflex camera (DSLR, Canon EOS 6D), a 50 mm lens, and a linear polarising filter (polariser) were used to determine PLP. The camera measures the radiance for each pixel (Jechow *et al*., 2019) in the three colour channels RGB (red, green, blue). PLP is determined by capturing two RGB images with different polariser orientations. The polariser orientations were set by identifying the lowest and the highest light transmission at a defined polarising reference surface (procedure in Fig. 2b). Both orientations were marked with a pencil on the camera lens to note the stops at which the rim should no longer move to obtain measurements. The camera was placed on a tripod at each measurement site to add stability, as no difference should occur from one frame to the other. The camera was then pointed towards the illuminated bridge. Note that the measurement (a linearly polarised map) should include the water surface in front of the illuminated bridge and the bridge itself. Also, the camera should remain in the set position for both orientations. Once the camera's position was determined, the polariser was set at 0°, and a measurement was obtained. The procedure was also repeated for the polariser set at 90°. A remote control was used to avoid moving the camera from position and to avoid misalignments. Note that the polariser must be carefully moved to avoid abrupt changes between the frames. ISO settings were fixed at 6400 and the shutter speed at 1/30 seconds. The camera was equipped with a GPS to record images of their corresponding locations within the 10 km transect. For comparing images, orientations 0° and 90° were considered enough to determine the PLP at the water surface. To calculate the PLP, the software R, with the packages named raster and sp for image processing (Raster: Geographic Data Analysis and Modeling, https://cran.r-project.org/package=raster; Sp: Classes and Methods for Spatial Data; https://cran.r-project.org/web/packages/sp/index.html), was used. The RAW (or CR2 format) files are then organised by measurement sites to extract RGB channels from each image. RAW files with the polariser set at 0° and 90° were used throughout this work. However, the full dataset also includes orientations 45° and 135°, which were shown to be not necessarily due to the relatively straightforward determination of the polarising plane (horizontal water surface).

Calculating PLP

The images taken at orientations 0° and 90° are used to determine the degree of linear polarisation (DOLP) of ALAN.

DOLP is given by:

$$DOLP_{0/90} = \left|\frac{I_0 - I_{90}}{I_0 + I_{90}}\right| \quad \text{(eq. 1)}$$

or using the stokes parameters

$$S_0 = I_0 + I_{90} \quad \text{(eq. 2)}$$

$$S_1 = I_0 - I_{90} \quad \text{(eq. 3)}$$

to shorten it to:

$$DOLP_{0/90} = \left|\frac{S_1}{S_0}\right|. \quad \text{(eq. 4)}$$

DOLP results in a value between 0 and 1 (respectively in %) that quantifies how much of the light wave's electric field was aligned in a defined direction. A perfectly polarised light wave has a DOLP of 1 (100%), while an unpolarised light wave has a DOLP of 0 (0%). More physical background on polarisation and water surfaces is given in the Supplementary Material.

Pixel count analysis of the water surface

Image J and R studio were used to determine water surfaces and the fraction of water surfaces strongly affected by PLP (Supplementary Material). The threshold representing high DOLP was set to 60% and above (0.6 to 1.0 in the DOLP scale or the greenish and yellow pixels). This corresponds roughly to the range at which polarization sensitivity thresholds have been described for some mayfly species and it can be expected that this could also be the case for other nocturnal aquatic insects (Kriska *et al*., 2009).

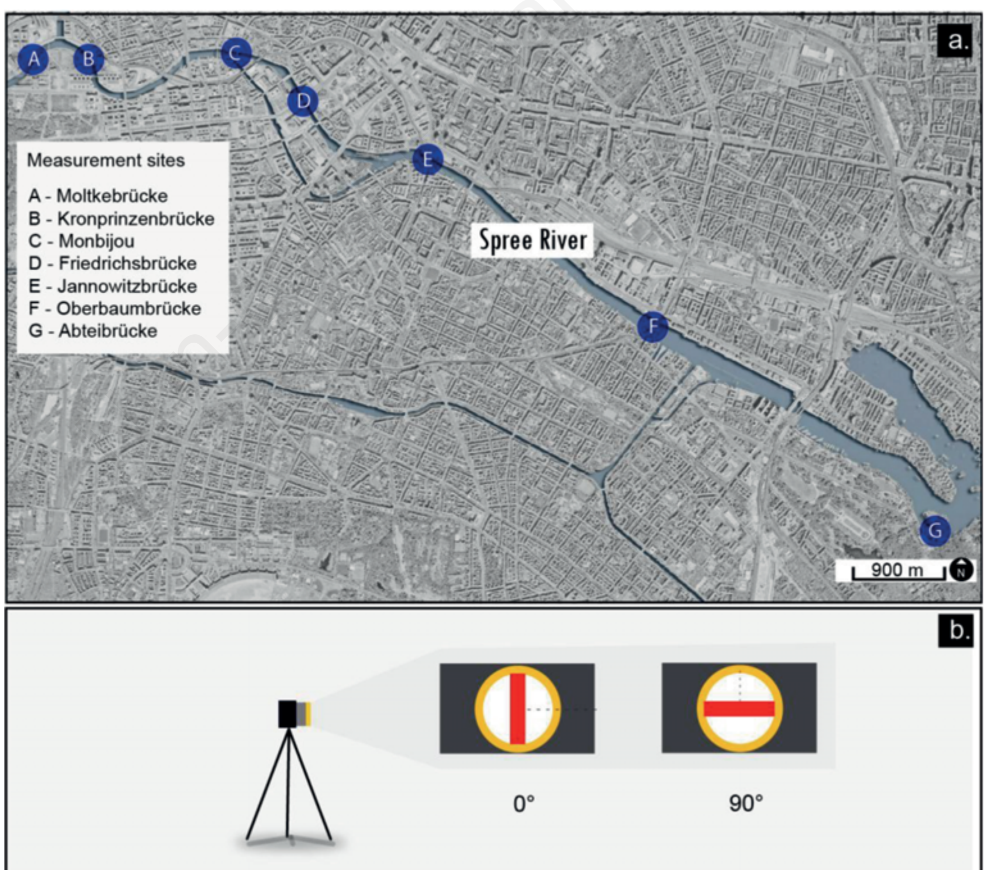

Fig. 2. a) Map of measurement sites indicating seven illuminated bridges on the river Spree, in Berlin, Germany. **b)** At each measurement site, an RGB camera is pointed at the illuminated bridge to obtain two images with a linear polariser in two different orientations: at 0° (vertical polarisation) and 90° (horizontal polarisation). Source: authors' own work.

RESULTS

Polarisation imaging was performed at each of the seven bridges and both RGB images and calculated DOLP maps (see methods) are presented in Figs. 3 to 9. Fig. 3 shows the imaging measurement results for Friedrichsbrücke (site D) as an example of the complete dataset. Fig. 3 a,b shows two RGB images for the two linear polarisations in which (a) corresponds to 0° (vertical polarisation) and (b) to 90° (horizontal polarisation). Also, RGB images show with magenta arrows the position of visible luminaires on the bridge, while the magenta squares indicate their reflected light at the water's surface. Blue arrows indicate the position of luminaires on the bridge for boat passage, while the blue squares indicate their reflected light at the water's surface. Fig. 3 c-e shows the calculated DOLP using eq. 4 (see METHODS section) for each pixel for the three colour channels of the camera (c, red; d, green and e, blue). The false colour code of each data image works as follows: greenish pixels have a high DOLP of nearly 100% (1.0), yellowish pixels are nearly 50% (0.5) DOLP, and reddish pixels have a low DOLP of nearly 0% (0.0). White pixels are removed data points where the original radiance was too low to properly extract a DOLP signal. At Friedrichsbrücke, both illumination types, for pedestrian (magenta arrows) and boat passage (blue arrows), induce horizontally polarised light by reflection (a DOLP ranging between 20% to 100%, on the water's surface. Also, the sources for both illumination types were directly visible from the measurement position.

For the other sites, only a reduced imaging data set with only one RGB image and calculated DOLP for each pixel of the blue

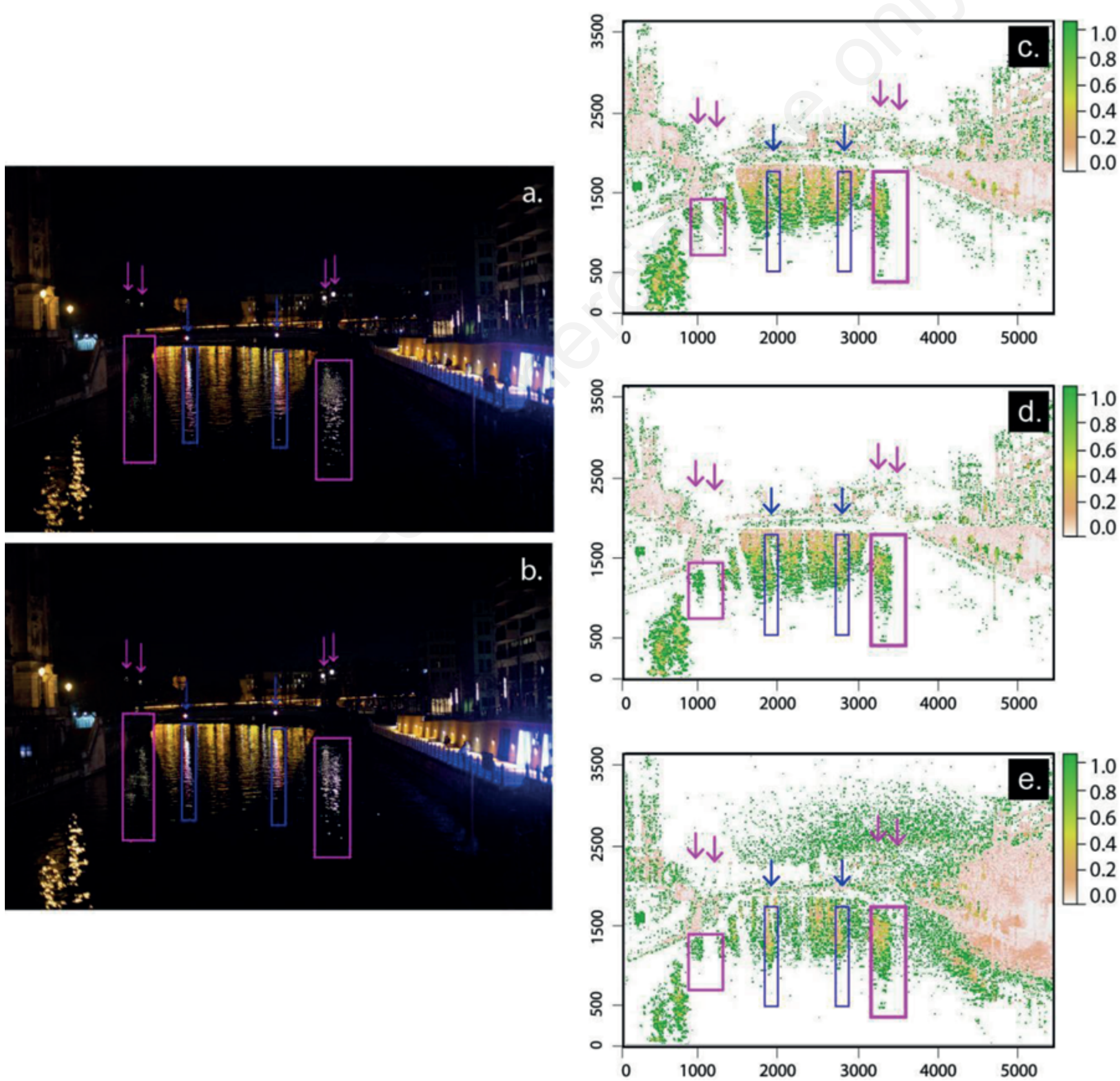

Fig. 3. **a,b)** RGB images of measurement site D (Friedrichsbrücke) where **(a)** shows polariser at 0° (vertical polarisation) and **(b)**, polariser at 90° (horizontal polarisation). own work Calculated DOLP (0.0-1.0 = 0-100%) for the red **(c)**, green **(d)**, and blue channel **(e)**. Arrows show dominant light sources and boxes show the reflected light on the water's surface.

colour channel is shown in Figs. 4 to 9. All measurements showed a strong DOLP signal for the blue channel, while the red channel had a weak DOLP signal. For the Moltkebrücke (site A, Fig. 4), both bridge illumination for pedestrian passage (magenta arrows) and for boat passage (blue arrows) induce horizontally polarised light by reflection (DOLP ranging between 20% to 100%) on the water's surface. Both luminaire types were visible from the measurement position. Also, indoor illumination from buildings in the vicinity of Moltkebrücke showed to induce PLP (DOLP ranging between 20% to 100%). However, these light sources were not directly visible from the measurement position (Supplementary Material).

For Kronprinzenbrücke (site B, Fig. 5) three illumination types with different functionalities (indicated with colours: magenta for pedestrians and vehicles; blue for boats; cyan for bridge decorative lighting; purple for a building behind the bridge; red for the floodlight under the bridge) were identified. Functional and decorative bridge lighting produced horizontally polarised light (DOLP ranging between 20% to 100%). At the bridge, three luminaires for pedestrians and vehicles, located on the opposite site of the measurement position and across the bridge (magenta arrows), were directly visible from across the bridge and induced horizontally polarised light (DOLP ranging between 80% to 100%) at the water surface. Two illuminating sources for boat passage (blue arrows), located at the bridge, were directly visible from the measurement position and also induced horizontally polarised light (DOLP ranging between 20% to 100%) at the water surface. Moreover, decorative lighting on the bridge (cyan arrow) created the most apparent horizontally polarised light by reflection (DOLP ranging between 20% to 100%), shown in the cyan box, compared to functional luminaires (magenta and blue arrows). The decorative lighting (cyan arrow) was also visible from the measurement position. In addition, far behind the bridge, a vertically illuminated wall (purple arrow) and a floodlight in the vicinity (red arrow) also created horizontally polarised light at the water surface. The light source of the vertically illuminated building was not visible from the measurement position (purple arrow), while the floodlight was visible and unshielded (red arrow). The building vertically illuminated upwards (DOLP ranging between 0% to 40%) presented a lower DOLP when compared to the floodlight with a visible light source (DOLP ranging between 20% to 100%) from the measurement position.

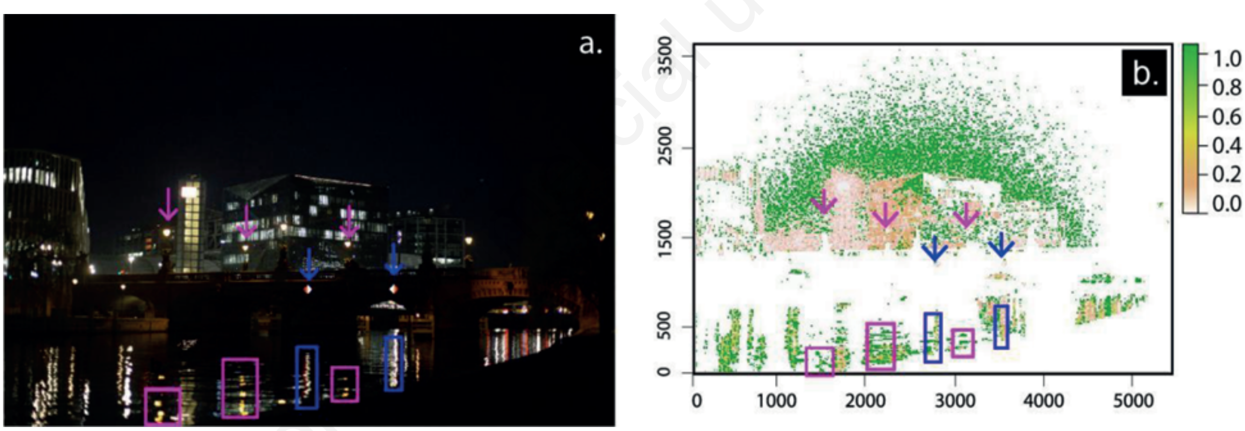

Fig. 4. a) RGB image of measurement site A (Moltkebrücke) with polariser at 90° (horizontal polarisation). **b)** Calculated DOLP (0.0-1.0 = 0-100%) for the blue channel own work. Arrows show dominant light sources and boxes show the reflected light on the water's surface.

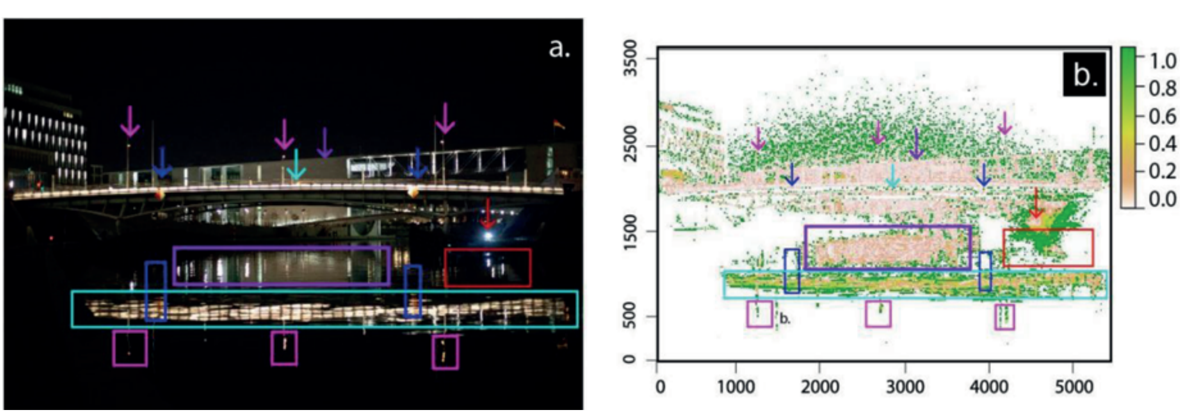

Fig. 5. a) RGB images of measurement site B (Kronprinzenbrücke) with polariser at 90° (horizontal polarisation). **b)** Calculated DOLP (0.0-1.0 = 0-100%) for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface.

At Monbijoubrücke (site C, Fig. 6), four illumination types: pedestrian lighting (magenta arrows), luminaires for boat passage (blue arrows), the TV tower with decorative lighting (cyan arrows), illuminated paths that surround the boroughs of the Monbijoubrücke (purple arrows), were identified as main sources of ALAN. Illumination for pedestrian and boat passage were directly visible from the measurement position, and both induced horizontally polarised light at the water surface (DOLP ranging between 20% to 60%). Berlin's iconic TV tower (cyan arrows), situated behind the bridge, is vertically illuminated upwards and induced horizontally polarised light, but had no light sources that were directly visible from the measurement position (apart from the red blinking lights used at the top of buildings for plane navigation). The illuminated TV tower presented a higher DOLP signal on the water surface (DOLP ranging between 20 to 100%) compared to bridge ALAN (magenta and blue arrows). In addition, surrounding illuminated paths (purple arrows) created a weak DOLP signal. The light sources of the surrounding paths were directly visible on the left side, but non-visible on the right side.

At Jannowitzbrücke (site E, Fig. 7), three illumination types, for pedestrians and vehicles (magenta arrows), for boats (blue arrows), and surrounding illumination from a building were identified. All three types cause horizontally polarised light (DOLP ranging between 20 to 100%) at the water surface. The surrounding illumination showed a DOLP signal compared to luminaires for pedestrians, vehicles and boats, which were all visible from the measurement position. Five illumination types were identified at Oberbaumbrücke (site F, Fig. 8), luminaires for vehicles (magenta arrows), boats (blue arrows), decorative purposes that include light projected on the walls of a tower to show its architecture and textures (cyan arrows), and the Universal building that included a backlit (illuminated from behind) logo and a vertical uplit (luminaires directed upwards) wall (purple arrows). Luminaires for vehicles were not visible from the measurement position but induced horizontally polarised light (DOLP ranging between, 40 to 100%) at the water surface. Luminaires for boats were visible from the measurement position and caused horizontally polarised light by reflection (DOLP ranging between 40 to 100%) at the water surface. The light sources that projected light on the two top towers were not visible from the measurement position and its direct DOLP signal was weak compared to other illuminated structures. Still, it showed a signal of horizontally reflected polarised light at the water surface (DOLP ranging be-

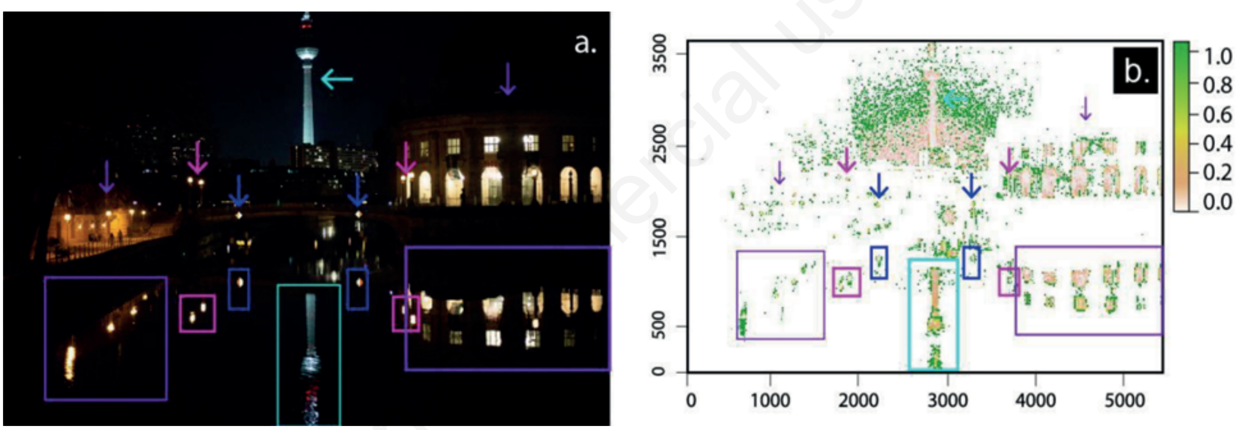

Fig. 6. a) RGB images of measurement site C (Monbijoubrücke) with polariser at 90° (horizontal polarisation). **b)** Calculated DOLP (0.0-1.0 = 0-100%) for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface.

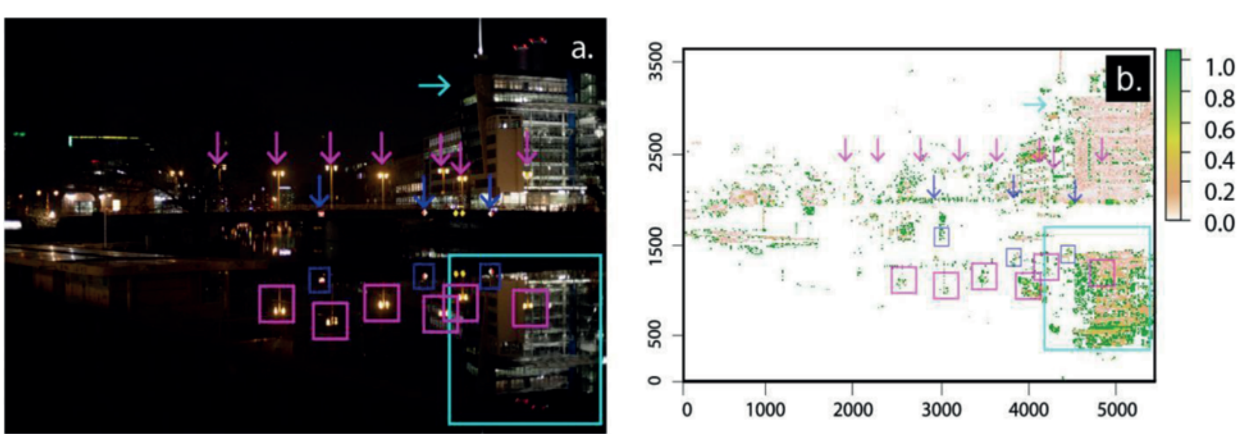

Fig. 7. a) RGB images of measurement site E (Jannowitzbrücke) with polariser at 90° (horizontal polarisation). **b)** Calculated DOLP (0.0-1.0 = 0-100%) for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface.

tween 60 to 100%). The illumination from the Universal building (both the Universal logo and the uplit wall) produced that broadest DOLP signal (DOLP ranging between 20 to 100%) that horizontally polarised reflected light at the water surface when compared to other sources at Oberbaumbrücke. The light sources of the Universal logo were somehow visible from the measurement position due to the glass structure while the light sources of the uplit wall remained not visible.

Two illumination types were identified at Abteibrücke (site G, Fig. 9), bridge luminaires for pedestrians (magenta arrows) and luminaires for pedestrians at the shore in a distance (cyan arrows). Both types of pedestrian illumination showed to horizontally reflect polarised light at the water surface (DOLP ranging between, 20 to 100%). The light sources of both illuminating scenarios were visible from the measurement position.

The fraction of high PLP pixels (DOLP >60%) of the total water pixels was calculated for each site and is shown in Fig. 10. For all sites, a fraction between 3% and 13% of the water surfaces appeared to be strongly polluted by ALAN-induced polarised light. Friedrichsbrücke had the highest fraction of ALAN-induced PLP, with 13% of the water surface having a high DOLP signal. Moltkebrücke had 12%, Kronprinzenbrücke 11%, Jannowitzbrücke 9%, Oberbaumbrücke 8%, and Abteibrücke 7% of high DOLP signal at the water surface. The lowest fraction of high DOLP was determined at Monbijoubrücke with 3%. Thus, on average around 9% (SD=3.4) of the investigated water surfaces appear to be affected. Note that these percentages are solely based on the point in time and space where measurements were taken. See also Tab. S2 and Fig. S4 on DOLP signal on the water surface.

DISCUSSION

This study, performed at the river Spree in Berlin, shows that illuminated bridges and the illuminated urban surroundings create ALAN-induced PLP that can mask the natural polarisation signal of natural light incident on rivers by night. Moreover, surrounding illuminated areas showed, when the 3-RGB channels were observed separately, that a strong DOLP signal was present for the blue channel while a weak DOLP signal appeared for the red channel. Moreover, a strong polarisation signal was present in the blue channel of four bridges (Moltkebrücke, Friedrichsbrücke, Kronprinzenbrücke, and Monbijoubrücke), shown in

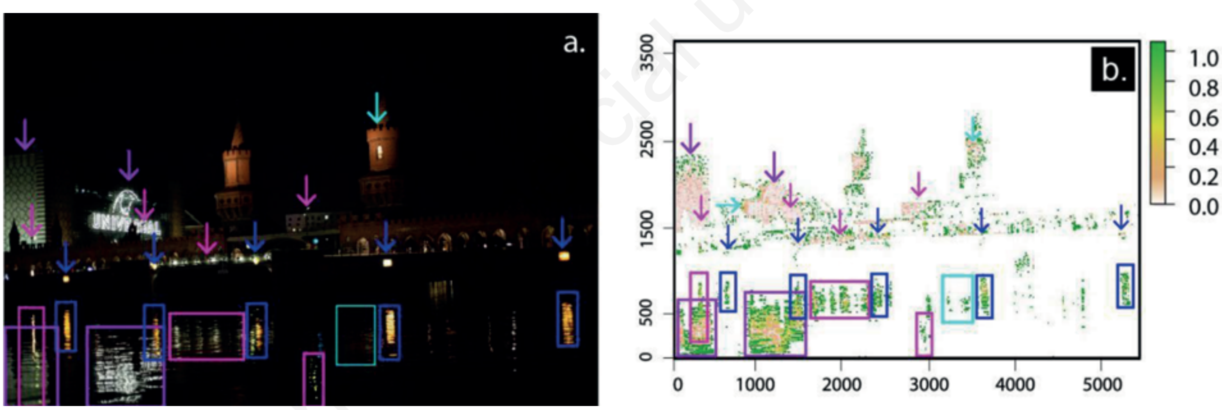

Fig. 8. **a)** RGB images of measurement site F (Oberbaumbrücke) with polariser at 90° (horizontal polarisation). **b)** Calculated DOLP (0.0-1.0 = 0-100%) for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface.

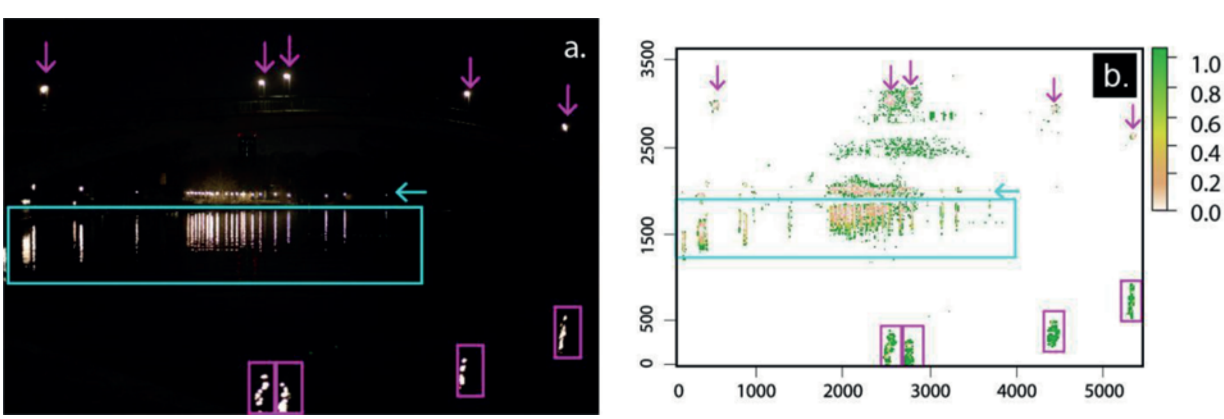

Fig. 9. **a)** RGB images of measurement site G (Abteibrücke) with polariser at 90° (horizontal polarisation). **b)** Calculated DOLP (0.0-1.0 = 0-100%) for each imaging pixel for the blue channel. Arrows show dominant light sources and boxes show the reflected light on the water's surface.

Figs. 3e, 4b, 5b, and 6b, while a weak DOLP signal appeared for the red channel when the 3-RGB channels were observed separately. This observation suggests the potential presence of reflected short wavelengths (at water surfaces or other polarising surfaces) from surrounding illumination.

The pixel analysis of the water surfaces unravelled that on average around 9 % (SD=3.4) of the water surfaces near the studied bridges are heavily polluted by polarised light (d >60%). This PLP is radiated into the perspective of flying insects, which may misinform polarotactic insects about the characteristics of a particular habitat. For example, strongly and horizontally polarised light, as found near bridges in our study, is a quite stable optical cue for dark/deep waters under natural conditions (Horvath and Csabai, 2014).

A recent daytime study by Szás *et al*. 2023 on DOLP of sunlight reflected from a dark patch of a lake showed higher DOLP in the blue spectral range (450±50 nm) compared to the red spectral range (650±50 nm). This is in line with our observations. The polarisation of reflected moonlight has been much less studied than sunlight reflected from water surfaces. However, studies mention that the distribution and properties of moonlight resemble those of sunlight simply with different intensity (Cronin and Marshall, 2011). Consequently, flying aquatic insects could be attracted closer to areas illuminated with cold-white light (i.e. with broad spectral range rich in short wavelengths) as the polarisation sensitivity of aquatic insects have been shown to rely often on short wavelengths and as the DOLP of reflected light from natural waters has been shown to be highest at short wavelengths (Schwind, 1995; Bernáth *et al*., 2004).

At the bridges, we mainly observed unshielded bridge ALAN, including individuals and groups of luminaires, that produce a high amount of PLP. Mostly the heads of post-top luminaires had no proper shielding. Only at Oberbaumbrücke, the bridge illumination for vehicles were not directed towards the water surface. This made the light sources not visible from the measurement position and resulted in a lower DOLP signal on the water surface. Our measurement results were mainly in line with our anticipation that bridge ALAN induces PLP, particularly if luminaires are unshielded. However, the result might differ if the viewing position at each bridge changes.

Surprisingly, ALAN from the surroundings observed to produce more PLP at the water surface than ALAN from the bridges and the bridge structures, apparent in Figs. 5 to 9b. ALAN from buildings in the vicinity created PLP, even when the point sources were not directly visible from the measurement position. For example, the vertically illuminated or light emitted upwards of the building behind Kronprinzenbrücke in Fig. 5 (purple arrow), the TV tower far behind Monbijoubrücke in Fig. 6, the building illuminated next to Jannowitzbrücke in Fig. 7, and the two light projected towers at the top of Oberbaumbrücke in Fig. 8. PLP was induced at both illuminated bridges and pathways in the proximity of the water surface, as well as in urban areas not immediately adjacent to the water surface. Other illumination scenarios, apart from bridge ALAN, that created PLP included nearby indoor

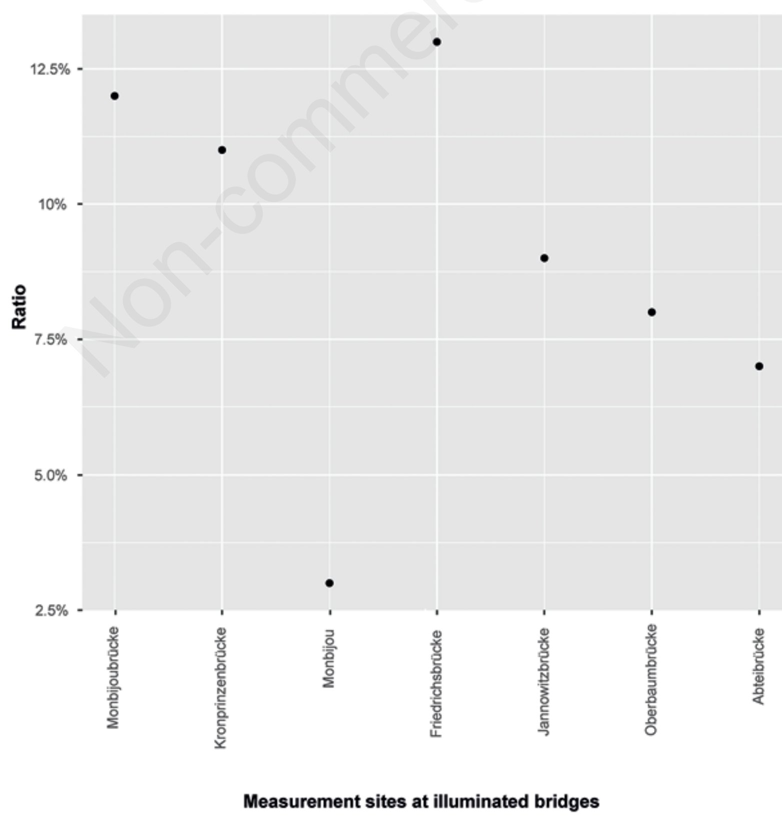

Fig. 10. Fraction of DOLP affected pixels with respect to total water pixels (in percent) for the seven illuminated bridges (DOLP water pixels/water pixels).

building illumination (Figs. 4 and 6), decorative bridge lighting (Fig. 6) and floodlights in the vicinity (Fig. 6).

In the past, most studies on PLP mainly focused on artificial surfaces (*e.g*., concrete, paint, glass, *etc*.) and even on daytime illumination, showing that man-made structures can become ecological traps (Horváth *et al*., 2014). Recent literature has demonstrated that artificial light sources, particularly at or near roadways close to waterways, are likely to disrupt natural light at night, as asphalt roads are also reflecting ALAN of a specific polarisation direction (Waterman, 1954; Horváth and Varjú, 1997). PLP is a phenomenon that has been shown to attract insects by luring them away from their typical trajectories into unsuitable habitats that can lead into an ecological trap towards reproductive failure or death (Turcsányi *et al*., 2009; Black and Robertson, 2020; Robertson and Chalfoun, 2016). These are just some of the known behavioural consequences for aquatic polarotactic insects when man-made structures appear to be polarising water surfaces (Szás *et al*., 2015; Egrí *et al.*, 2019; Horváth *et al*., 2014).

Sensory ecology on polarisation signals of aquatic insects dates back to the 1980s (Schwind, 1983), and research on polarisation signals in the hydrosphere dates back to the 1950s (Waterman, 1954), making the field a very recent one. In recent years it has gained the attention of the ALAN community and ecologists (Horváth *et al*., 2009; Szás *et al*., 2015, 2023) as it has been shown to be related to behaviours in the insect organism group. In recent studies, ALAN, as a source of PLP and a potential nocturnal evolutionary trap for aquatic insects, has become a subject of concern (Egri *et al.*, 2019; Fraleigh *et al.*, 2021; Turcsányi *et al*., 2009). In this study, we filled this research gap by showing that PLP also occurs in urban aquatic nightscapes, induced by luminaires close to the water surface (*e.g*., bridge ALAN) that are improperly shielded and by surrounding illumination that creates light pollution due to the improper management of its light distribution. Please note that our procedure (taking multiple images in a row) has the drawback that the water surface undergoes small changes from one image to the next (*e.g*., small ripples due to wind or movement of animals or boats). Therefore, the (more correct) use of all four images 0°, 45°, 90° and 135° created more noise than additional information would have been included when using all Stokes parameters (Foster *et al.,* 2018). However, a test run with a still water surface comparing the DOLP with all four and the reduced two Stokes parameters showed equivalent results because of the known horizontal orientation of the water surface (which cannot be easily omitted for built structures like concrete). Studies have demonstrated different approaches to measuring polarised light. Shashar *et al*. (1995) demonstrated an approach to polarisation sensors, imaging polarimetry with DSLR cameras and a polarising filter (Horváth and Varjú, 1997; Egrí *et al*., 2017), and most recently, Száz *et al*. (2023) used drones for imaging polarimetry. In our study, the process is hindered by the removal and placement of the polarisation filter, which is not recommended. This would change if multiple cameras or a specific polarisation measurement camera (Szás *et al*., 2023) that can obtain all polarisation orientations in a single image would have been used. In such a case, the use of all Stokes parameters to unravel even more information is recommended.

Like sunlight, moonlight produces polarised light patterns at night (though more than six orders of magnitude weaker than sunlight) that can be perceived ideally on cloudless nights (Gál *et al*., 2001). Moonlight polarisation has been described as a band of highly polarised light across the sky at a 90-degree angle from the moon that, if masked by light pollution, is likely to affect the navigation system of nocturnal animals (Gál *et al*., 2001; Kyba *et al*., 2011). In a natural pristine river, where only the moonlight may be visible starlight, lunar polarisation not only in the sky but also from reflected light is expected to be an important orientation cue, as shown in Fig. 1. If the moon polarisation signal is masked by ALAN (often multiple light sources of ALAN), then ALAN can misinform polarotactic organisms as shown in Fig. 11. Insects can thus be attracted to streetlamps that emit unpolarised light, but also be misled by polarised light reflected from the water surface. Thus, PLP can interfere with optically encoded polarimetric signals and thus affect the perceptibility and interpretation of information about the night sky and adjacent aquatic habitats for polarotactic organisms.

Wetlands and waterbodies are important interfaces that aquatic insects need to detect to complete their life cycles successfully. Both fully aquatic insects (adults and larvae are mainly aquatic) and insects with terrestrial adult stages, but aquatic larvae or nymphs use horizontal polarisation of light by means of reflection to detect their habitat (reviewed in Horváth, 2014). This also applies to aquatic insects in the river Spree. These include *e.g*. Chironomidae (38 species) and other Diptera (20 species), Odonata (23 species), Trichoptera (38 species) and Ephemeroptera (20 species) (Köhler *et al*., 2002). Non-biting midges, particularly female chironomids, are known to use horizontally polarised light by reflection to detect breeding habitats (Lerner *et al*., 2008, 2011). Coleoptera, Heteroptera, Ephemeroptera and dragonflies swarm and mate over surfaces that are horizontally polarised light by reflection (Wildermuth and Horvéth, 2005; Bernáth *et al*., 2022). Deteriorating the natural polarisation signals can misinform specific light conditions, habitat location, detection of water surface, selection of habitats and oviposition sites, alter communication, predator and prey detection and even affect reproductive success (Schwind, 1991; Kriska *et al*., 2006 Lerner *et al*., 2011; Szás *et al*., 2015; Egrí *et al.*, 2019).

Recommendations for future ALAN research and urban lighting

PLP remains a pollutant reported only in few biological studies as polarisation is a novel entity rarely considered in night-time environments, and our knowledge of the negative implications of PLP is still very limited (Horváth *et al*., 2009; Hölker *et al*., 2023). Therefore, future ALAN research should explore polarisation as a property of light, as various animals are able to perceive it. Also, polarisation should be further explored to properly assess the use and application of ALAN and materials to avoid masking the natural polarisation signal of moonlight after dusk.

Furthermore, the urban lighting design field is still centred on parameters that solely consider human visual orientation and visibility based on daytime vision and apply light in that manner across nightscapes (Pérez Vega *et al*., 2022). ALAN becomes present in areas where it is not needed, as the practice still remains unaware of properties of light, such as polarisation, that are not used by humans but that are crucial for other organisms to survive.

Lastly, to protect organisms sensitive to reflected polarised light, it is recommended that the emission of luminaires shall not exceed the intended functional range, and, if possible, the water bodies should remain unlit throughout the night by shielding solutions for luminaires (Hölker *et al*., 2023). This is to avoid flying aquatic insects being lured into a PLP zone, the boundaries between the bridge structure, or into the asphalt road, all unsuitable places to lay eggs (Kriska *et al*., 1998; Egri *et al*., 2017, 2019; Bernáth *et al*., 2004).

The perception of water bodies by flying aquatic insects has been shown to be related to the properties of polarised reflected light of short wavelengths – ultraviolet (UV) radiation (Schwind, 1989; Fraleigh *et al*., 2021), blue wavelengths and green wavelengths (Schwind, 1995). Luminaires near water bodies could, therefore, be adapted to reduce critical wavelengths in order to mitigate the attraction of positively phototactic insects that are sensitive to short wavelengths and polarised light. However, it should be noted that many aquatic animals use the entire visible spectrum. Consequently, protective measures such as improving luminance distribution or reducing light intensity and duration are likely to be more effective in minimising the negative impacts of polarised light on freshwater biodiversity (Hölker *et al*., 2023).

CONCLUSIONS

Our study highlights bridge ALAN as a source of PLP for aquatic habitats even when the source is not directly visible from the observation point. If ALAN reaches the water's surface, this can induce polarised light that can mask natural polarisation cues, which probably can become an ecological hazard for flying aquatic insects and other polarotactic organisms sensitive to changes in polarised light. Our literature scan unravels a large knowledge gap on PLP and ALAN in the context of aquatic systems. More research on this optical pollutant is required to aid professionals in the lighting field and representatives of the lighting industry in addressing the United Nations Sustainable Development Goal (SDG14) (SDG14, 2015) for the protection of aquatic life and habitats. While our pilot study is limited to single-point measurements, more comprehensive measurements across different environments and urban gradients are required. This can be achieved with better imaging tools (Szás *et al*., 2023) from aerial vehicles (Szás *et al*., 2015) or from boats (Pérez Vega *et al*., 2023). While our knowledge of ALAN as a pollutant has increased, the behavioural responses of organisms sensitive to polarised light still need more research to be better and properly understood.

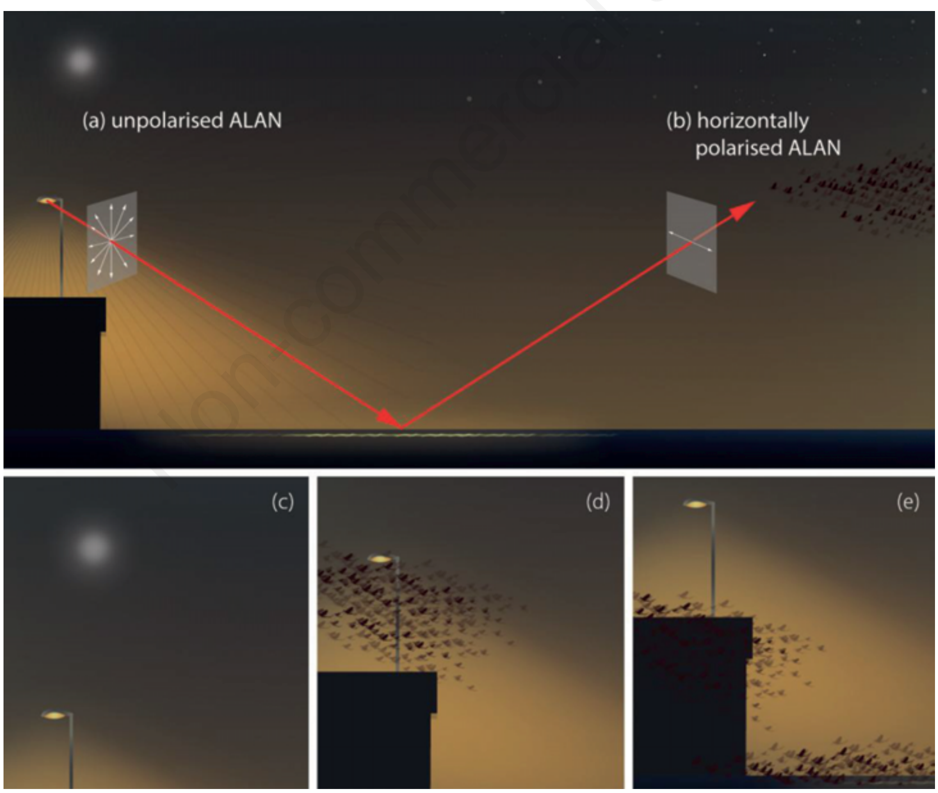

Fig. 11. a) Unpolarised light can become polarised when interacting with a surface or orientated particles. **b)** Polarisation at surfaces is a result of Fresnel reflection at *e.g.* the interface of air and water, which is when unpolarised light (in the air) reaches the surface of the water and becomes *e.g.* horizontally polarised *via* reflection. If ALAN is unpolarised and incident on a polarising surface (*e.g.* water, asphalt), then this can result in ALAN-induced polarised light pollution (PLP). At a particular angle of incidence (Brewster's angle, 53° for air and water), the reflected light is fully polarised. ALAN-induced PLP, can mask lunar skylight polarisation **(c)**, or it might lure flying aquatic insects into the source of ALAN due to positive phototaxis and positive polarotaxis, potentially inducing a vacuum effect (Perkin *et al*., 2011; Hölker *et al*., 2023) at the artificial source of illumination **(d)**. Flying aquatic insects, could be misinformed by polarising surfaces like misinterpreting asphalt for water **(e)**, which can lead to reproductive failure or death. Source: authors' own work.

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Online supplementary material:

Fig. S1. Unpolarised and linearly polarised light reflected after passing through a polariser.

Fig. S2. Overview of incident light being polarised.

Fig. S3. Plot of the reflection coefficients as a function of angle of incidence.

Fig. S4. Total and high DOLP water pixels.

Tab. S1. Position at which measurements were taken at each site.

Tab. S2. Pixel count on the total amount of pixels on the water's surface of each measurement site.