ENVIRONMENTAL REMEDIATION TECHNOLOGIES, REGULATIONS AND SAFETY

ASPHALT SURFACES AS ECOLOGICAL TRAPS FOR WATER-SEEKING POLAROTACTIC INSECTS: HOW CAN THE POLARIZED LIGHT POLLUTION OF ASPHALT SURFACES BE REDUCED?

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PREFACE

The surface of dry or wet asphalt roads reflects partially linearly polarized light, the degree of linear polarization p of which depends on the darkness and roughness of asphalt: the darker and/or the smoother the asphalt, the higher the p of light reflected from it. If the asphalt is sunlit and the direction of view is parallel to the solar-antisolar meridian, then the direction of polarization of asphalt-reflected light is horizontal. In this case the asphalt surface can attract water-seeking aquatic insects, because they detect water by means of the horizontal polarization of light reflected from the water surface. This phenomenon is called positive polarotaxis. Polarotactic insects mistaking asphalt surfaces for water bodies lay their eggs upon dry asphalt after copulation, where the eggs perish due to dehydration. The polarization signal of the asphalt surface can be so strong that insects can actively prefer asphalt over water as an oviposition site. This phenomenon is well studied for mass-swarming mayflies, but other polarotactic insects, such as dragonflies, caddisflies, stoneflies, water beetles and aquatic bugs can also be deceived by and attracted to asphalt roads near natural water bodies. We refer to the negative survival and reproductive consequences of artificial sources of polarized light on polarotactic organisms as polarized light pollution. Highly and horizontally polarizing asphalt roads are sources of polarized light pollution that can create ecological traps for polarotactic insects when they become more attractive than natural habitats. Trapped populations are predicted to have a high probability of extinction, and so paved surfaces may threaten populations of endangered aquatic insect species. An ecological trap for water insects can further trigger a secondary ecological trap for other vertebrate species that prey upon the water insects attracted to the asphalt: these insects and the carcasses of vehicle-killed polarotactic insects can attract different

insectivorous vertebrates, especially birds, which can also be run down by the cars. In this work we study the polarizing characteristics of asphalt surfaces as functions of the surface features (roughness, darkness, painted with white striates or not), the illumination conditions (sunny or shady), and the direction of view relative to the solar meridian. On the basis of these data we suggest some possible strategies to mitigate the severity of polarized light pollution produced by asphalt. In areas with gravel roads, for example, change of the gravel to the more insect-attracting asphalt should, if possible, be avoided. We show how the degree of polarization *p* of asphalt-reflected light can be reduced under the threshold of polarization sensitivity of aquatic insects: the roughness, brightness and white-striateness of the asphalt surface should be increased in order to reduce *p*, and thus the attractiveness to polarotactic insects. We propose the use of these remedies on asphalt roads running near emergence sites of endangered aquatic insects, especially in the vicinity of wetlands, rivers and lakes. Conservation biologists may effect substantial benefits for aquatic insects and their ecosystems by working with asphalt road planners to reduce the attractiveness of asphalt surfaces to polarotactic species.

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Chapter 1

INTRODUCTION: POLAROTACTIC INSECTS ATTRACTED TO ASPHALT ROADS AND POLARIZED LIGHT POLLUTION OF ASPHALT SURFACES

1.1. ATTRACTION OF POLAROTACTIC AQUATIC INSECTS TO DRY ASPHALT ROADS

Ladócsy (1930) observed that mayflies (*Palingenia longicauda*) swarming above the river Tisza in Hungary were attracted to a wet asphalt road running parallel to the river. Puschnig (1926), Bromley (1928), Fraser (1936) and Whitehouse (1941) reported that different dragonfly species patrolled along dry asphalt roads instead of rivers and showed a stereotypical water-touching behaviour on the asphalt surface. Kriska *et al*. (1998) observed that near sunset mayflies swarmed, mated above and landed on a dry asphalt road running in the immediate vicinity of their emergence site, a mountain streamlet (Figure 1). After copulation females laid their eggs on the dry asphalt surface instead of ovipositing them on the water surface. Near mountain creeks, female stoneflies with their egg-batches could also often be seen on the asphalt road. These observations showed that the mayflies and stoneflies were apparently deceived by and attracted to the dry asphalt surface.

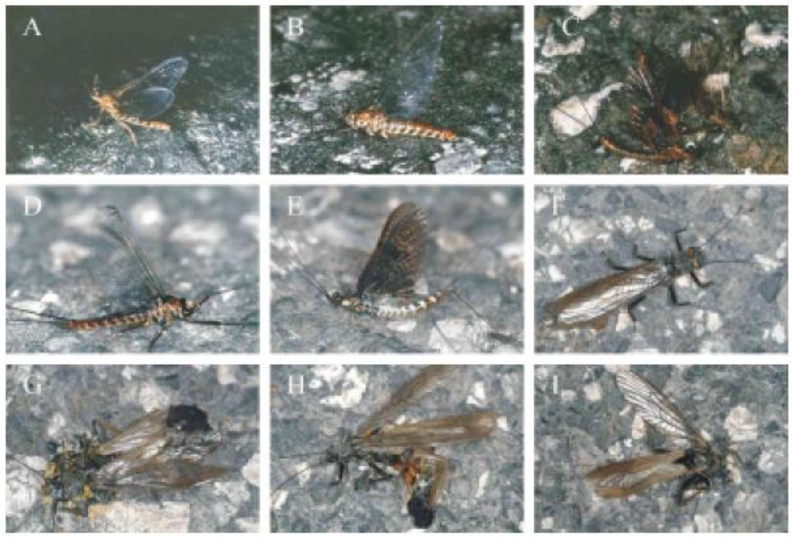

Figure 1. Examples of aquatic insects attracted to and landed on a dry asphalt road in the immediate vicinity of a mountain creek near Budapest, Hungary in June 1997 (A-C) and 2008 (D-I). (A) A male *Rhithrogena semicolorata* mayfly. (B) A female *Epeorus silvicola* mayfly. (C) A female and two male *Epeorus silvicola* attempting to mate. (D) A male *Epeorus silvicola*. (E) A male *Ephemera danica* mayfly. (F) A female *Perla burmeisteriana* stonefly. (G-I) Carcasses of female *Perla burmeisteriana* run over by cars.

Kriska *et al*. (1998) revealed the reasons for this strange behaviour: In multiple-choice field experiments they showed that mayfly species detect water by means of the horizontal polarization of water-reflected light, and thus possess positive polarotaxis, i.e. they are attracted to horizontally polarized light. They found that the darker and smoother the asphalt surface, the greater is its attractiveness to polarotactic mayflies. Imaging polarimetry revealed that, when mayflies swarm at sunset asphalt surfaces mimic a highly and horizontally polarizing water surface to water-seeking mayflies. The highly and horizontally polarizing asphalt roads with relatively homogeneous distributions of the degree and direction of polarization of reflected light are much more attractive to polarotactic mayflies than water surfaces. An asphalt surface can reflect and polarize the incident light in such a way that the reflected light becomes a supernormal stimulus for water-seeking mayflies in comparison to the light reflected from water. Multiple-choice experiments showed that highly and horizontally polarizing shiny black plastic sheets create this same phenomenon. A relatively small (a few

m^2) shiny black plastic sheet attracted all the mayflies swarming above the asphalt road within several tens of metres (Kriska *et al*., 1998).

Night-migrating water-seeking polarotactic insects can be attracted to streetlamps above dry asphalt roads by positive phototaxis. As they approach the lamplit asphalt, they can also perceive the asphalt-reflected horizontally polarized light, and can be compelled to remain temporarily in the light spots on the asphalt (Figure 2), if the polarized light signature is strong enough.

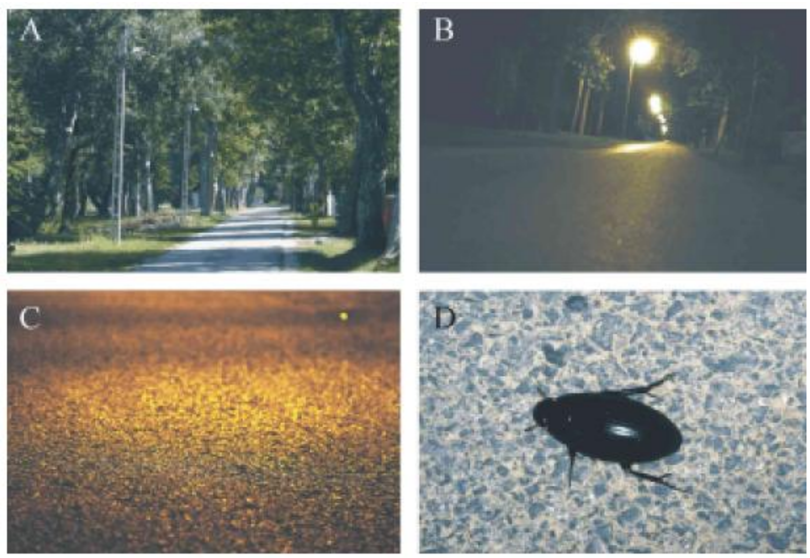

Figure 2. (A) The asphalt road in daylight on the beach of lake Balaton (at Balatonszemes, Hungary), where at night aquatic beetles have been observed to land on the lamplit dry asphalt surface. (B) The same asphalt road at night. The polarized light pollution of this road illuminated by streetlamps at night is synergetically supported by the conventional photopollution of the lamps: night-flying polarotactic aquatic insects are first lured by positive phototaxis to the streetlamps, then they are attracted to the highly and horizontally polarized light reflected from the asphalt. (C) A lamplit asphalt surface at night. (D) A great silver diving beetle (*Hydrophilus piceus*) attracted by a streetlamp and landed on the dry asphalt below the lamp.

The major aim of this work is to present new experimental data about the reflection-polarization characteristics of various asphalt surfaces to understand the conditions under which positively polarotactic insects can be attracted to asphalt.

1.2. Polarized Light Pollution and Polarized Ecological Traps

It is a well-known fact that the degradation of human views of the night sky in and near cities makes practically all astronomical observations impossible. The stars and other celestial bodies are washed out by artificial lights that are either directed or reflected upward. This phenomenon is called the 'astronomical light pollution' (Riegel, 1973; Upgren, 1996; Wilson, 1998; Cinzano *et al*., 2001; Rich and Longcore, 2006, p. 3). On the other hand, the term 'ecological light pollution' is used to describe all kinds of 'photopollution' (a synonym of 'light pollution') which disrupts ecosystems and cause disturbances to natural behaviours in various animals (Verheijen, 1958, 1985; Longcore and Rich, 2004, 2006; Rich and Longcore, 2006). Ecological light pollution has been defined by Verheijen (1958, 1985) as the "degradation of the photic habitat by artificial light". It involves direct glare, chronically increased illumination, and temporary, unexpected fluctuations in lighting. Its sources include sky glow, lighted structures (e.g., buildings, towers, bridges), street lights, security lights, lights of vehicles and fishing boats, flares on offshore hydrocarbon platforms, and lights on undersea research vessels (Rich and Longcore, 2006, pp. 3-4). Both the documented and possible ecological consequences of artificial night lighting were comprehensively summarized in the monograph edited by Rich and Longcore (2006).

The first effects of artificial night lights is the attraction, or repulsion of animals by the spatiotemporally enhanced intensity of light relative to the dark environment. This phenomenon, called positive or negative phototaxis, is elicited by the intensity and/or colour of artificial light. Phototaxis has been considered as the major visual phenomenon underlying the ecological light pollution. Horváth *et al*. (2009) introduced the term 'polarized light pollution' (PLP) as a new kind of ecological photopollution. PLP refers to highly and horizontally polarized light reflected from smooth (shiny) artificial surfaces having adverse effects on polarotactic aquatic insects, including all insects, the larvae of which live in water (e.g., aquatic beetles and water bugs, dragonflies, mayflies, caddis flies, stoneflies, tabanid flies and mosquitoes).

Most species of aquatic insects (e.g., Ephemeroptera, Odonata, Plecoptera, Trichoptera) must return to water to lay their eggs. Water bodies also often serve as rendezvous sites for both sexes of aquatic insects. As orientation in aquatic insects is predominantly visual, we may ask for the optical cues by which specific water bodies are recognized. Rudolf Schwind (1983a,b, 1984a,b, 1985a,b) discovered that the water bug, backswimmer (*Notonecta glauca*) detects water by means of the horizontally polarized light reflected from the water surface (Schwind and Horváth, 1993), rather than by the intensity or colour of water-reflected light, or by the glittering, or mirroring of the water surface. In the ventral eye region of *Notonecta* Schwind *et al*. (1984) found ultraviolet-sensitive photoreceptors with horizontal and vertical microvilli being highly sensitive to horizontally and vertically polarized light (Schwind, 1983b). These orthogonally polarization-sensitive photoreceptors are able to determine whether the direction of polarization of light from the optical environment is horizontal or not. In *Notonecta* an exactly or nearly horizontally polarized light stimulus elicits a typical plunge reaction (Schwind, 1984b), a form of positive polarotaxis.

The ventral eye region in many aquatic insects is also sensitive to the polarization of light in the visible or ultraviolet spectral ranges (Schwind, 1991, 1995). These insects find their habitat on the basis of the horizontally polarized light reflected from the water surface (Horváth, 1995; Gál *et al*., 2001a). Aquatic insects detect polarization in that region of the spectrum, which is characteristic of their preferred habitat (Schwind, 1995). Depth, turbidity, transparency, colour, surface roughness of the water and substratum composition as well as the illumination strongly influence the reflection-polarization characteristics of water bodies (Horváth and Varjú, 2004). Polarized light reflected by water provides important information on the quality of freshwater habitats for polarotactic insects and can aid the orientation of these insects from a distance when other cues (e.g., air humidity, dimension and shape of the water body, undulation of the water surface, water plants on the surface and the shore, temperature and odour) are still ineffective.

In a series of observations Schwind (1985a,b, 1989, 1991, 1995) showed that several species of aquatic bugs and beetles are positively polarotactic. Later studies (Kriska *et al*., 1998, 2006a, 2007, 2008; Horváth *et al*., 1998, 2007, 2008; Wildermuth, 1998, 2007; Bernáth *et al.*, 2001a; Wildermuth and Horváth, 2005; Csabai *et al.*, 2006; Lerner *et al*., 2008; Boda and Csabai, 2009a,b; Turcsányi *et al*., 2009) found that beside aquatic bugs and beetles, other water insects like dragonflies, mayflies, tabanid flies, caddis flies and chironomid mosquitoes exhibit positive polarotaxis when searching for water. More than 300 polarotactic aquatic insect species are known that recognize their aquatic habitat by horizontally polarized water-reflected light (Horváth and Kriska, 2008). Presently, the only known aquatic insect species that does not select its aquatic oviposition site by means of polarotaxis is the yellow fever mosquito, *Aedes aegypti* (Bernáth *et al*., 2008). Thus, apart from *A. aegypti*, it is quite understandable that polarotactic insects can be deceived by and attracted to every artificial surface that reflects highly and horizontally polarized light; polarized light can function as a supernormal behavioural stimulus. The physical (1), behavioural (2) and ecological (3) bases of PLP are the following:

According to the rule of Umow (1905), the darker a surface in a given part of the spectrum, the higher the degree of linear polarization *p* of light reflected from it. Since diffuse reflection from rough (matte) surfaces results in depolarization, the smoother (the shinier) a surface, the higher the *p* of reflected light. Since the direction of polarization of light reflected from smooth dielectric materials is always perpendicular to the plane of reflection, if this plane is exactly or nearly vertical, the reflected light is exactly or approximately horizontally polarized. From these it follows:

(1) Smooth and dark artificial surfaces with exactly/nearly vertical plane of reflection reflect highly and exactly/nearly horizontally polarized light.

The higher the *p* of light and the less deviates its direction of polarization from the horizontal, the greater its attractiveness to polarotactic aquatic insects (Horváth and Varjú, 2004). Consequently:

(2) Smooth and dark artificial surfaces with exactly/nearly vertical plane of reflection are highly attractive to polarotactic insects.

Aquatic insects attracted to highly and horizontally polarizing dry artificial surfaces may perish due to dehydration, or may oviposit onto these surfaces where their eggs fail to hatch. Thus:

(3) Highly and horizontally polarizing artificial surfaces may act as 'polarized ecological traps' for ovipositing polarotactic aquatic insects *sensu* Schlaepfer *et al*. (2002) and Robertson and Hutto (2005), because such surfaces are more attractive, but less suitable for survival and reproduction than natural habitats.

Modern human development has resulted in the introduction of different sources of PLP to natural habitats. In the natural optical environment only the flat water surface reflects horizontally polarized light, the *p* of which is high if light is reflected from dark water bodies at the Brewster angle

(Horváth and Varjú, 2004). Today, PLP is mainly a byproduct of the human architectural, building, industrial and agricultural technology. The phenomenon of PLP is global and new in an evolutionary sense, having increased rapidly only over the last decades, following the spread of highly and horizontally polarizing artificial surfaces such as oil spill lakes and open-air oil reservoirs, asphalt roads, plastic sheets, glass surfaces and cars, for example. PLP is a well-documented cause of adult and egg mortality among aquatic beetles and bugs, mayflies and caddis flies (Horváth and Kriska, 2008), can alter the relationship among predators (e.g., spiders, birds and bats) and their insect prey, and even has potential to alter community composition (Horvath *et al.* 2008). PLP is also the most common cause of ecological traps, cases of maladaptive habitat selection in which organisms come to prefer the worst available habitat in terms of survival and reproductive success. Such cases are especially problematic in terms of conservation, because they are predicted to lead to rapid population declines, and possibly extinction (Delibes *et al*., 2001; Kokko and Sutherland, 2001). Consequently, PLP has great potential to threaten populations of endangered aquatic insect species.

PLP can occur not only in daytime, but also at night, if moonlight or city light (e.g., skyglow, streetlamps) is reflected from polarized-light-polluting surfaces. Vulnerability to PLP (based on positive polarotaxis) could be enhanced by the synergetical interaction with conventional photopollution (based on positive phototaxis) caused by artificial night lighting. PLP could also be influenced by lunar cycles, especially in rural environment, where artificial night lighting is rare or lacking. It is important to determine and monitor the sources of PLP in order to minimize and/or replace them by artificial surfaces which are "aquatic insect friendly". Since many human developments with numerous polarized-light-polluting artificial surfaces are near water bodies (Marsh and Grossa, 2002), the aquatic insects living in/at lakes, rivers, ponds and streams are all subject to PLP. Because aquatic insects are critically important as members of food webs in aquatic ecosystems, adverse effects of PLP on these animals could have serious ecological consequences.

Flight to horizontally polarized light reflected from artificial surfaces could disturb the ecology of aquatic insects, and often can lead to high mortality of the adults and/or the eggs laid onto these polarized-light-polluting surfaces. Polarotactic aquatic insects frequently are not able to escape from the source of PLP. We call this behaviour the "polarization captivity effect" *sensu* Eisenbeis (2006), which culminates in the death of insects due to dehydration and exhaustion. The migration, dispersal, mating and reproduction of aquatic insects can also be disturbed by sources of PLP encountered in their long-distance flight paths. We call this the "polarization crash barrier effect" *sensu* Eisenbeis (2006) because of the interruption of movement across the landscape. Aquatic insects are also vulnerable to normal (unpolarized) artificial lights: Scheibe (2000), for example, documented that streetlamps have a long-distance effect for light-susceptible mayflies and caddis flies emerging from a small mountain stream. The night-time attraction of these insects to lamps is so strong that if there were a row of streetlamps along a stream, a species could become locally extinct in a short time. This extinction can only be accelerated by PLP.

In this work we measured the light polarizing ability of asphalt roads, which phenomenon is responsible for the PLP of asphalt surfaces. We also show some simple ways to reduce, or even eliminate, the PLP of asphalt.

Chapter 2

METHOD: MEASURING THE POLARIZATION PATTERNS OF ASPHALT SURFACES BY IMAGING POLARIMETRY

Using theoretical calculations (Schwind and Horváth, 1993; Horváth, 1995; Horváth and Pomozi, 1997) and imaging polarimetry (Horváth and Zeil, 1996; Horváth and Varjú, 1997, 2004; Gál *et al*., 2001b; Mizera *et al*., 2001; Horváth *et al*., 1997, 2002; Bernáth *et al*., 2002, 2004; Malik *et al*., 2008), the reflection-polarization characteristics of water surfaces and artificial reflectors can be compared. Imaging polarimetry is a useful technique to establish and monitor the sources of polarized light pollution. In this work we used also this method to measure the reflection-polarization patterns of asphalt surfaces.

The reflection-polarization patterns of various asphalt surfaces were measured by imaging polarimetry in the red (650 nm), green (550 nm) and blue (450 nm) parts of the spectrum. The method of imaging polarimetry was described in detail elsewhere (Horváth and Varjú, 1997; Mizera *et al*., 2001). Here we mention only the fact that when a linearly polarizing filter is rotated in front of a camera, the intensity and colour of the recorded scene change sinusoidally, if the incident light is partially linearly polarized. Taking three pictures from the scenery through the polarizer at three different orientations of its transmission axis, we obtain the so-called polarization pictures. After the evaluation of these pictures by an appropriate computer program, we obtain the two-dimensional spatial distributions of the intensity I, degree of linear polarization p, and angle of polarization α (e.g., from the vertical, as a reference direction,) of light coming from the investigated scenery in the red, green and blue spectral range, where the camera's detectors are maximally sensitive.

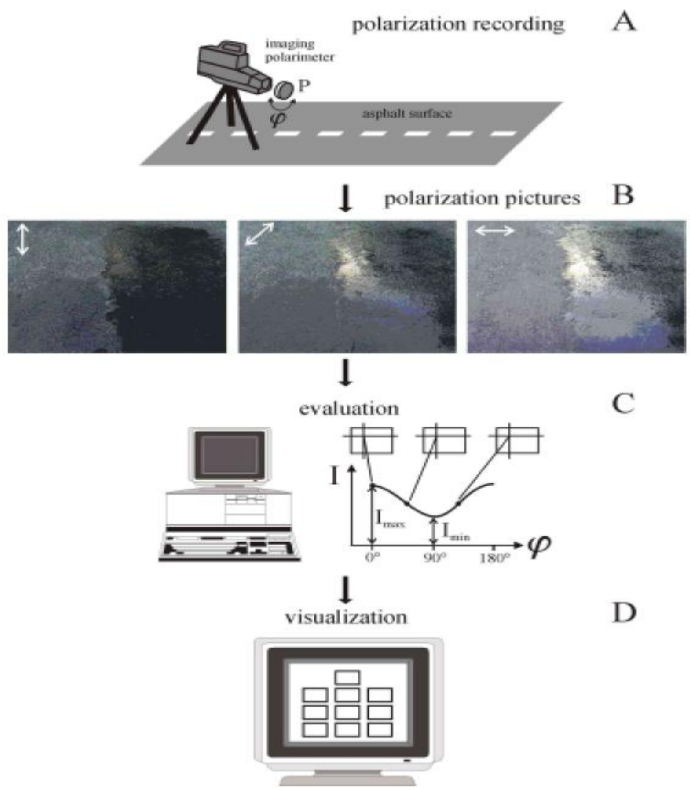

Figure 3. Schematic representation of the method of imaging polarimetry. (A) Recording the polarization pictures: three pictures of the scene are taken by a camera through a linearly polarizing filter (P) with three different directions (angles $\varphi = \varphi_1, \varphi_2, \varphi_3$ from the vertical) of its transmission axis. (B) The three polarization pictures of an asphalt surface (left half: dry, right half: wet, top half: rough and bright, bottom half: smooth and dark), where double-headed arrows show the directions of the polarizer's transmission axis. (C) Computer evaluation of the recorded polarization pictures. (D) Visualization of the measured polarization patterns on the computer monitor.

Figure 3 shows schematically the method of imaging polarimetry. The first step (Figure 3A) is the recording of the polarization pictures: three pictures of the scene are taken by a camera through a linearly polarizing filter P with three different directions (angles $\varphi = \varphi_1, \varphi_2, \varphi_3$ from the vertical) of its transmission axis. Figure 3B shows three polarization pictures of an asphalt surface; the double-headed arrows represent the directions of the polarizer's transmission axis. The left half of the asphalt was dry, while its right half was wet. Furthermore the top half was rough and bright, while the bottom half was smooth and dark. The third step in imaging polarimetry is the computer evaluation of the recorded polarization pictures, and the fourth (and last) step is the visualization of the measured polarization patterns on the computer monitor.

We measured the reflection-polarization patterns of several different asphalt surfaces (rough/smooth, dark grey/light grey, black/white-painted) in Hungary and Sweden under different meteorological conditions (clear/cloudy sky, sunny/shady and dry/wet asphalt) and from different directions of view relative to the solar meridian. The optical axis of the imaging polarimeter from the horizontal was also different.

Chapter 3

RESULTS

3.1. POLAROTACTIC AQUATIC INSECTS OBSERVED TO LAND ON ASPHALT ROADS

During our field experiments, performed almost every year from 1997 at an asphalt road running in the vicinity of a mountain creak near Dömörkapu, we observed that mayflies and stoneflies are deceived by and attracted to the asphalt surface, on which they land and lay their eggs in large numbers. The mayflies perform typical reproductive behaviour above the asphalt road: the males swarm above the asphalt, display species-specific nuptial dances, chase the females flying through the male swarms and copulate. Details of these behaviours are described in detail elsewhere (Kriska et al., 1998). Figure 1 shows some examples of the mayflies and stoneflies attracted to and landed on the dry asphalt road investigated. The male *Rhithrogena semicolorata* and the female and male *Epeorus silvicola* mayflies in Figure 1A-1C were photographed in June 1997, while the male *Epeorus silvicola* and *Ephemera danica* mayflies, the female *Perla burmeisteriana* stoneflies and their carcasses crushed by cars in Figure 1D-1I were photographed in June 2008.

The eggs laid by mayflies and stoneflies on the dry asphalt inevitably perish within about an hour due to dehydration. Similarly, if female mayflies and stoneflies crawling on the asphalt road are crushed by cars (Figure 1G-1I), their egg-batches perish too. Every year we also observed that white and yellow wagtails (*Motacilla alba* and *M. flava*) systematically feed on the mayflies and stoneflies attracted by the asphalt road. These birds either chase and capture the insects flying above the asphalt, or pick up the insects landed on the asphalt, or their carcasses. This behaviour of wagtails on asphalt roads was quite similar to that observed on huge shiny black plastic sheets laid onto the ground and used frequently in agriculture (Bernáth and Horváth, 1999; Bernáth *et al*., 2001b). During feeding on asphalt roads the birds are in danger due to the car traffic. Some carcasses of wagtails hit by cars were also observed by us at the investigated asphalt road.

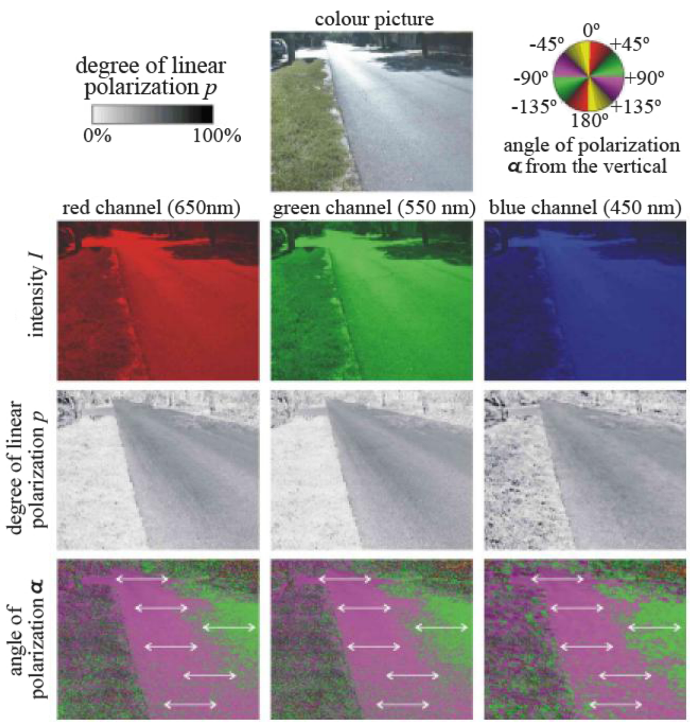

Figure 4. Colour picture and patterns of the intensity *I*, degree of linear polarization *p* and angle of polarization α (clockwise from the vertical) of light reflected from a sunlit, partly shady, dry asphalt road measured in the red (650 nm), green (550 nm) and blue (450 nm) parts of the spectrum by imaging polarimetry. The polarimeter viewed toward the solar meridian, and the angle of elevation of its optical axis was -35^{o} from the horizontal. The grey and colour codes of *p* and α are shown by the insets in the topmost row. The darker the grey tone, the higher is *p*. Red colours, for example, code angles of polarization $0^{o} \leq \alpha < 45^{o}$. Regions reflecting exactly ($\alpha = \pm 90^{o}$) or nearly ($\alpha \approx \pm 90^{o}$) horizontally polarized light are shaded by bright green and violet colours in the lowermost

row, in which the double-headed arrows show the local direction of polarization of reflected light.

On an asphalt road running parallel to the beach of the Hungarian lake Balaton we observed in July 2005 that at night great silver diving beetles (*Hydrophilus piceus*) were lured by positive phototaxis by the streetlamps. They landed on the dry asphalt road, where they crawled for 5-10 minutes (Figure 2), and finally left the road, or flew away. Some of them returned several times to the asphalt surface illuminated by streetlamps. It is pertinent to assume that the latter reaction might have been elicited by the highly and horizontally polarized asphalt-reflected light (positive polarotaxis), because these beetles also detect water by the horizontally polarized reflected light (Bernáth *et al*., 2001a). Thus the polarized light pollution of this road illuminated by streetlamps at night is synergetically supported by the conventional photopollution of the lamps: night-flying polarotactic aquatic insects are first lured by positive phototaxis to the streetlamps, then they are attracted to the highly and horizontally polarized light reflected from the asphalt. Figure 2A shows the asphalt road in daylight on the beach of lake Balaton at Balatonszemes, where at night the great silver diving beetles have been observed to land on the lamplit dry asphalt road. In Figure 2B the same asphalt road is seen at night. Figures 2C and 2D show the lamplit asphalt surface and a great silver diving beetle attracted by a streetlamp and landed on the asphalt below the lamp.

3.2. Reflection-Polarization Characteristics of Asphalt Surfaces

Our above observations, some other earlier reports on dragonflies attracted to asphalt roads (Puschnig, 1926; Bromley, 1928; Fraser, 1936; Whitehouse, 1941), and the fact that so many taxa of aquatic insects (e.g. mayflies, stoneflies, diving beetles and dragonflies) possess positive polarotaxis (Schwind, 1991, 1995; Horváth and Varjú, 2004), inspired us to measure the reflection-polarization characteristics of different asphalt surfaces under various illumination conditions by means of imaging polarimetry.

Figure 4 shows the colour picture and the patterns of the intensity *I*, degree of linear polarization *p*, and angle of polarization α of light reflected from a sunlit, partly shady, dry asphalt road measured in the red (650 nm), green (550 nm) and blue (450 nm) parts of the spectrum by imaging polarimetry. Angle α is measured clockwise from the vertical throughout this work. The polarimeter viewed toward the solar meridian, and the angle of elevation of its optical axis was -35^o from the horizontal. In Figure 4 we can see that the polarizing characteristics of the asphalt surface are practically independent of the wavelength of light, because the grey asphalt is colourless. We will present only the polarization patterns measured in the green (550 nm) part of the spectrum. The third row in Figure 4 shows that the degrees of polarization *p* of light reflected from the investigated asphalt road are much higher than those reflected by the surrounding grass. The *p*-pattern of the asphalt road is slightly inhomogeneous: darker/brighter asphalt regions reflect light with higher/lower *p*. It is clear from the fourth row of Figure 4 that the studied asphalt road reflected exactly ($\alpha = \pm 90^o$) or nearly ($\alpha \approx \pm 90^o$) horizontally polarized light (encoded by bright green and violet colours).

Figure 5 shows the reflection-polarization patterns of a sunlit dry asphalt surface from four different directions of view relative to the solar meridian: viewing (i) toward the solar meridian, (ii) clockwise perpendicularly to the solar meridian with sun at the left hand side with 45^o solar elevation, (iii) toward the antisolar meridian, and (iv) anti-clockwise perpendicularly to the solar meridian with sun at the right hand side at 45^o solar elevation. This figure demonstrates well that the intensity and the polarization characteristics of asphalt-reflected light depend strongly on the direction of view. The asphalt looks the brightest and reflects sunlight with the highest degree of polarization *p* when viewed toward the solar meridian, furthermore the reflected light is horizontally polarized (Figure 5A). When viewed toward the antisolar meridian, the asphalt reflects relatively weakly and again horizontally polarized light (Figure 5C). On the other hand, viewed perpendicularly to the solar meridian, *p* of asphalt-reflected sunlight is low, and its direction of polarization is tilted (Figure 5B, 5D): if the sun is at the left/right hand side, the direction of polarization tilts anti-clockwise/ clockwise (left/right) from the horizontal (Figure 5B/5D).

Figure 6 shows the reflection-polarization patterns of a sunlit, partly shady dry asphalt road running eastward for three different solar directions: when the sun was shining (1) from the left hand side, (2) in the face of the polarimeter, and (3) from the right hand side. Here we can see again that the asphalt reflects highly/weakly polarized light when viewed toward the solar meridian/antisolar meridian (see middle row in Figure 6). Furthermore sunlit asphalt reflects horizontally polarized light if viewed toward the solar meridian (Figure 6B), and the direction of polarization of light reflected from sunlit asphalt is tilted left (Figure 6A) and right (Figure 6C) from the horizontal when the sun is at left and right, respectively. However, the shady asphalt regions (illuminated only by skylight) always reflect horizontally polarized light (see last row in Figure 6).

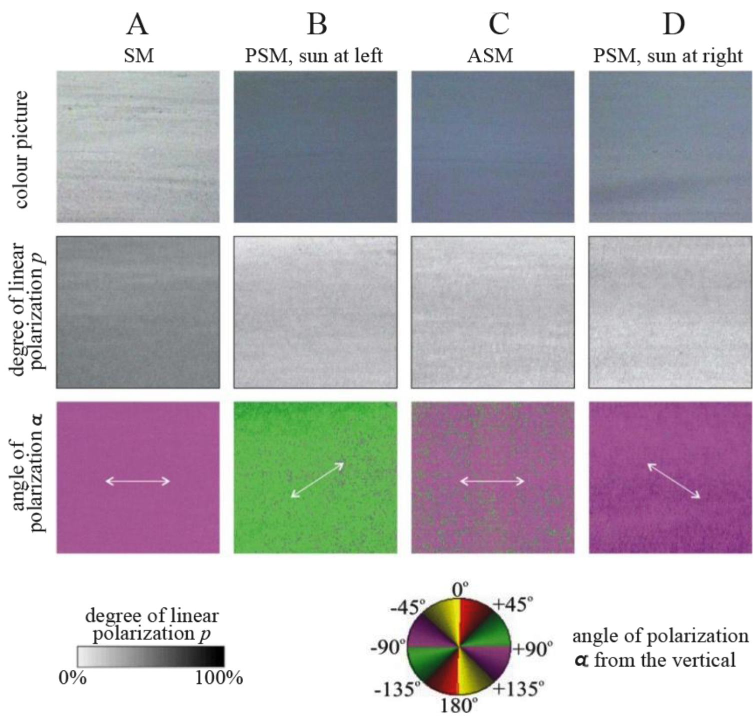

Figure 5. Reflection-polarization patterns of a sunlit dry asphalt surface from four different directions of view relative to the solar meridian measured in the green (550 nm) part of the spectrum. The angle of elevation of the polarimeter's optical axis was -35^o from the horizontal. In the lowermost row the double-headed arrows show the local direction of polarization of reflected light. (A) Viewing toward the solar meridian (SM). (B) Viewing clockwise perpendicularly to the solar meridian (PSM) with sun at the left hand side with 45^o solar elevation. (C) Viewing toward the antisolar meridian (ASM). (D) Viewing anti-clockwise perpendicularly to the solar meridian (PSM) with sun at the right hand side at 45^o solar elevation.

In Figure 7 we can see the reflection-polarization patterns of a dry asphalt surface if it is lamplit and sunlit when the polarimeter viewed toward the source of light (streetlamp, sun) and the angle of elevation of its optical axis was the same (-20^o from the horizontal). This figure demonstrates that an asphalt surface always reflects horizontally polarized light when viewed toward the direct source of light, which can be a streetlamp, or the sun, for example.

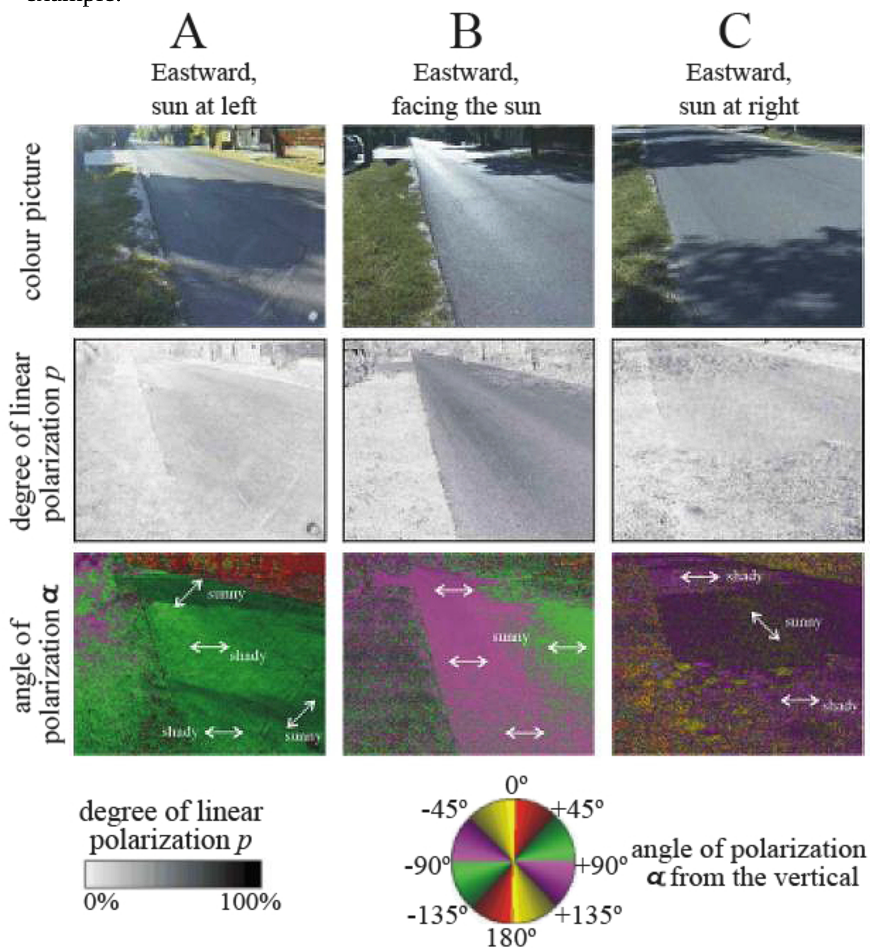

Figure 6. Reflection-polarization patterns of a sunlit, partly shady dry asphalt road running eastward measured in the green (550 nm) part of the spectrum for three different solar directions. The angle of elevation of the polarimeter's optical axis was -20^o from the horizontal. In the lowermost row the double-headed arrows show the local direction of polarization of reflected light. (A) The sun was shining from the left hand side. (B) The sun was shining in the face of the polarimeter. (C) The sun was shining from the right hand side.

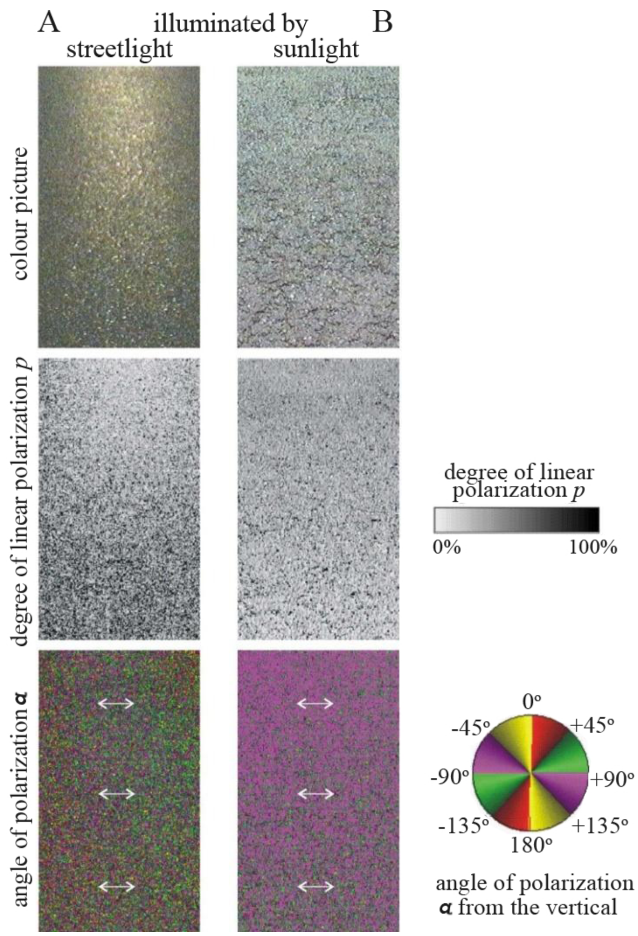

Figure 7. Reflection-polarization patterns of a dry asphalt surface when it is lit by streetlamps (A) and sunlight (B) measured in the green (550 nm) part of the spectrum. The polarimeter viewed toward the source of light (streetlamp, sun) and the angle of elevation of its optical axis was -20^{o} from the horizontal. In the lowermost row the double-headed arrows show the local direction of polarization of reflected light.

Figure 8 shows the reflection-polarization patterns of two different sunlit dry asphalt surfaces viewed toward the solar meridian with the same angle of elevation (-35^{o} from the horizontal) of the polarimeter's optical axis. In Figure 8A the left half of the road was brighter than the right one, because the left/right half was composed of old/new asphalt. We can see that brighter/darker asphalt surfaces reflect light with lower/higher degrees of polarization. In Figure 8B a rectangular part of the old rough (matte) asphalt surface was replaced by new smooth (shiny) asphalt. Here it is clearly shown that shiny (smooth) asphalt surfaces reflect highly polarized light, while matte (rough) asphalt surfaces reflect weakly polarized light. In both cases of Figure 8 the asphalt reflected horizontally polarized light (see last row in Figure 8), because the viewing direction pointed toward the solar meridian.

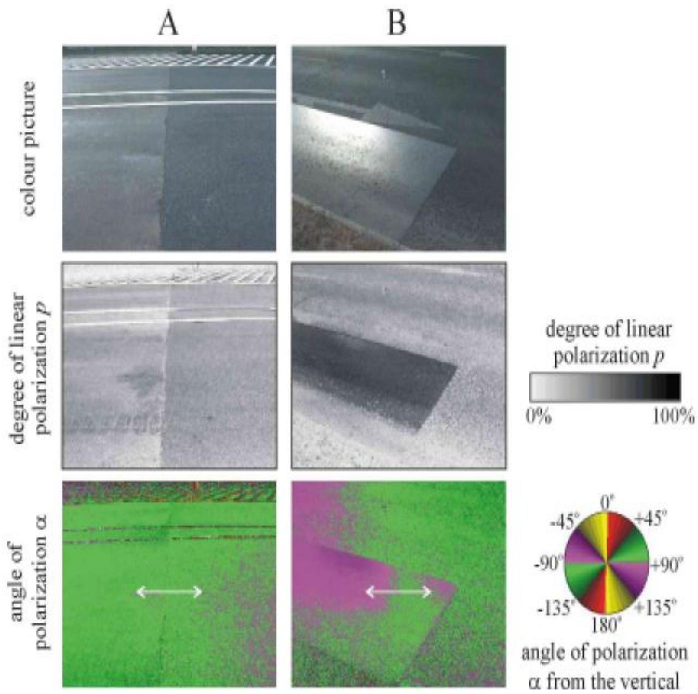

Figure 8. Reflection-polarization patterns of two different sunlit dry asphalt surfaces measured in the green (550 nm) part of the spectrum. In both cases the polarimeter viewed toward the solar meridian, and the angle of elevation of its optical axis was -35^{o} from the horizontal. In the lowermost row the double-headed arrows show the local direction of polarization of reflected light. (A) The left half of the asphalt surface is brighter than the right one, because the left/right half is composed of old/new asphalt. On the top part of the colour picture white guide lines on the road are visible. (B) Here a rectangular part of the old rough (matte) asphalt surface was replaced by new smooth (shiny) asphalt. On the top and middle parts of the colour picture white arrows as guide marks on the road are visible.

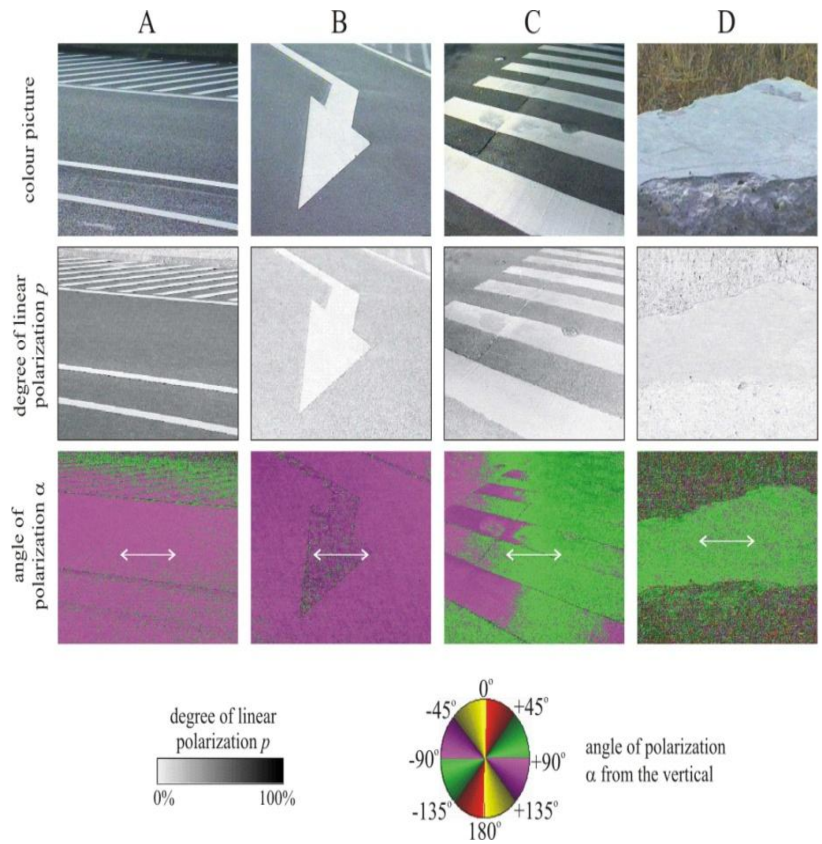

Figure 9. Reflection-polarization patterns of three different sunlit dry asphalt surfaces (A-C) and a concrete surface (D) measured in the green (550 nm) part of the spectrum. The polarimeter viewed toward the solar meridian, and the angle of elevation of its optical axis was -35^{o} from the horizontal. In the lowermost row the double-headed arrows show the local direction of polarization of reflected light. (A) Asphalt with white guide lines. (B) Asphalt with a white arrow guide mark. (C) Asphalt with white zebra stripes. (D) A light grey concrete block with horizontal surface.

Figures 9A, 9B and 9C represent the reflection-polarization patterns of sunlit dry asphalt surfaces with white guide lines, a white arrow guide mark and white zebra stripes. Figure 9D shows a light grey concrete block with a horizotal surface. In all four cases the polarimeter viewed toward the solar meridian, and the angle of elevation of its optical axis was -35^{o} from the horizontal. We can see in the middle row of Figure 9 that the white paint of the guide lines/marks and zebra stripes (commonly used on asphalt roads) and the light grey concrete surface (used also frequently at roads) reflect light with very low degrees of polarization, while the asphalt itself reflects more or less polarized light, depending on its surface darkness and roughness. Here the reflected light was again horizontally polarized (last row in Figure 9), because the direction of view was toward the solar meridian.

Figure 10 shows the reflection-polarization patterns of an asphalt road with patches of smooth (shiny) and rough (matte) surfaces illuminated by skylight at sunset. In the *p*-pattern of Figure 10 we can see that the rougher the road surface, the smaller the degree of polarization *p* of asphalt-reflected light due to the depolarizing effect of diffuse reflection. If the road is illuminated by skylight, coming from all possible directions, the direction of polarization of asphalt-reflected light is always exactly or approximately horizontal, as seen in the α-pattern of Figure 10.

Figure 11 shows the reflection-polarization patterns of an asphalt surface with four different characteristics: the top left quarter was dry and rough, the top right quarter wet and rough, the bottom left quarter dry and smooth, while the bottom right quarter was wet and smooth. The three polarization pictures of this asphalt surface are shown in Figure 3B. The asphalt was illuminated by skylight at sunset. We can see in the last row of Figure 11 that, independently of its surface characterisics, the skylit asphalt reflects always horizontally polarized light. On the other hand, the degree of polarization *p* of asphalt-reflected light strongly depends on the surface features (middle row in Figure 11): (i) *p* of light reflected from wet asphalt is much higher than that reflected from dry asphalt, furthermore (ii) smooth asphalt polarizes the reflected light stronger than rougher one. In the *p*-pattern of Figure 11 it is also clearly seen that the asphalt-reflected light is totally and horizontally polarized (with p = 100% and $\alpha = 90^{o}$) at the Brewster angle, when the angle of reflection θ from the vertical is $\theta_{Brewster}$ = arctan(n) = 57.3^{o} for the refractive index $n \approx 1.56$ of asphalt. The larger the deviation $\Delta\theta = |\theta - \theta_{Brewster}|$ of the angle of reflection from the Brewster angle, the lower the *p* of asphalt-reflected light. If $\Delta\theta$ is small, the asphalt-reflected light is very highly (p <≈ 100%) and nearly horizontally polarized ($\alpha \approx 90^{o}$). This asphalt region is called the Brewster zone. All these features of the degree of polarization *p* of asphalt-reflected light are also well seen in Figure 11.

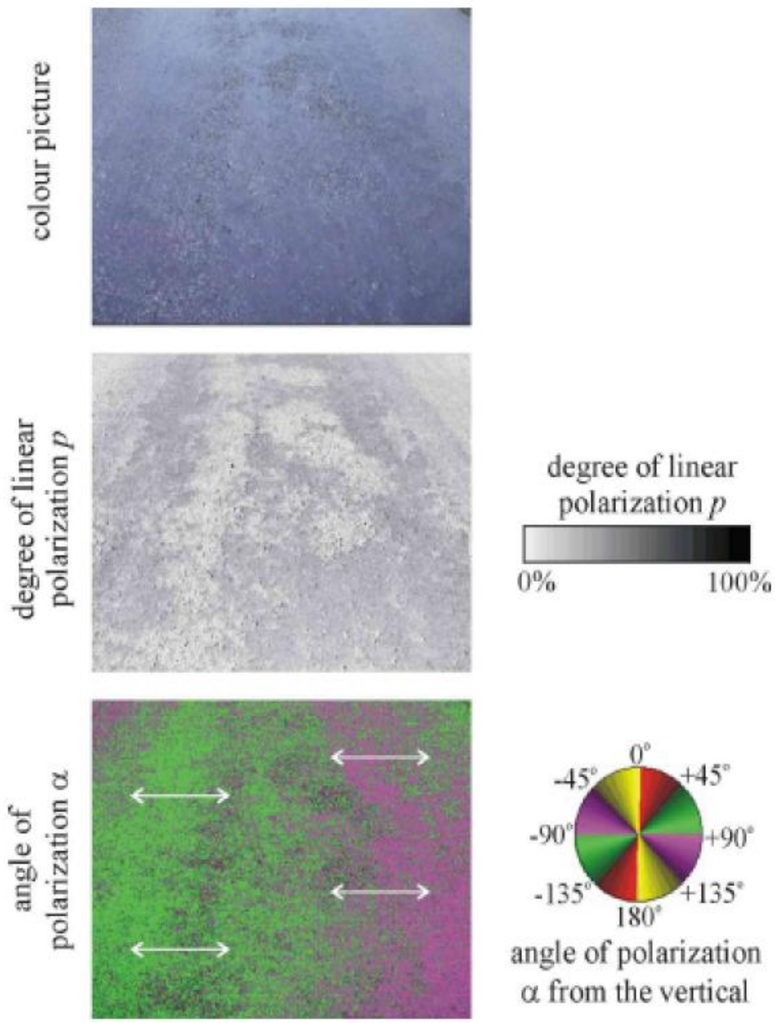

Figure 10. Reflection-polarization patterns of an asphalt road with patches of smooth and rough surface measured in the green (550 nm) part of the spectrum. The angle of elevation of the polarimeter's optical axis was -35^o from the horizontal, and the asphalt was illuminated by skylight at sunset. In the bottom row the double-headed arrows show the local direction of polarization of reflected light.

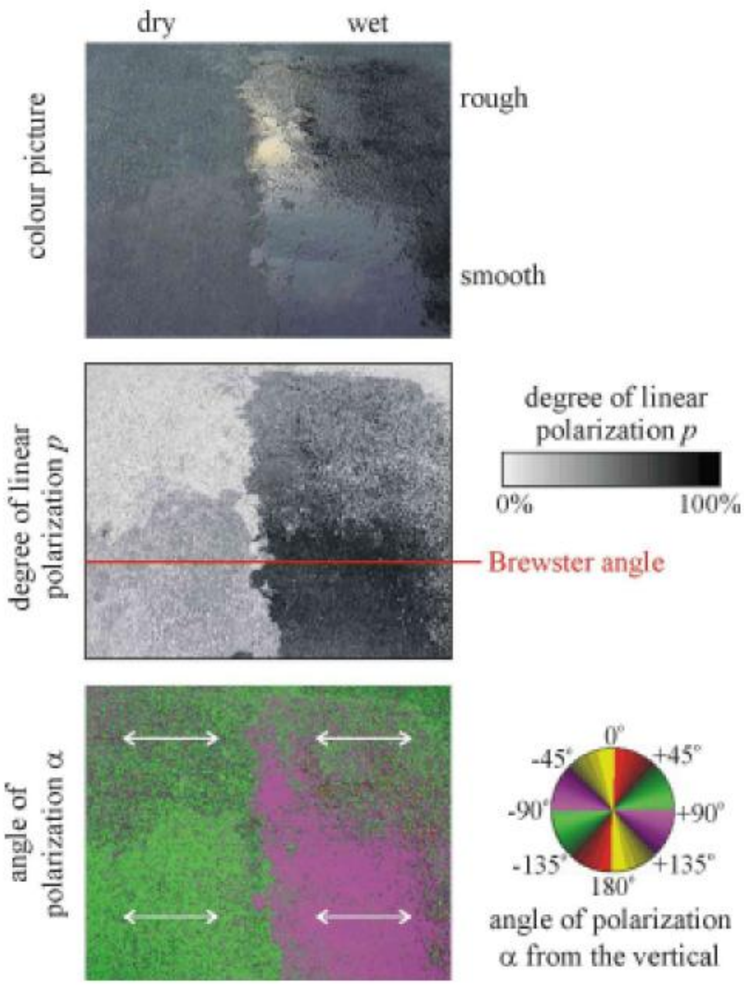

Figure 11. Reflection-polarization patterns of an asphalt surface with four different characteristics (top left quarter: dry and rough, top right quarter: wet and rough, bottom left quarter: dry and smooth, bottom right quarter: wet and smooth) measured in the green (550 nm) part of the spectrum. The angle of elevation of the polarimeter's optical axis was -35^{o} from the horizontal, and the asphalt was illuminated by skylight at sunset. In the lowermost row the double-headed arrows show the local direction of polarization of reflected light. Directions of view corresponding to the Brewster angle ($\theta_{Brewster} = 57.3^{o}$ from the vertical) of asphalt are represented by a horizontal red line. The three polarization pictures of this scene are shown in Figure 3B.

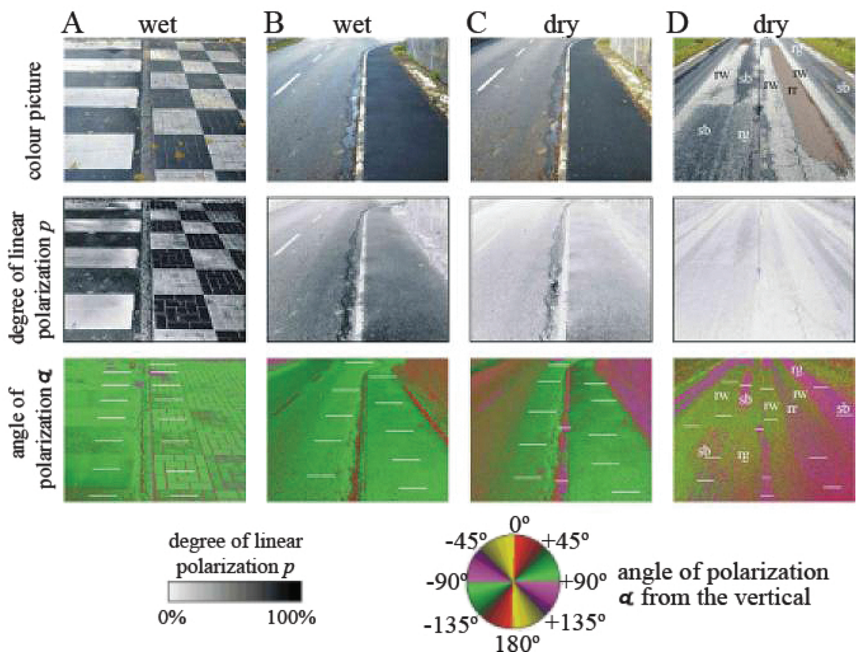

Figure 12. Reflection-polarization patterns of four different asphalt surfaces under overcast skies measured in the green (550 nm) part of the spectrum. The angle of elevation of the polarimeter's optical axis was –35° (A) and –20° (B-D) from the horizontal. In the lowermost row the white bars show the local direction of polarization of reflected light. (A) A wet asphalt surface with two different white-black chequered patterns. (B) A wet light grey asphalt road with a wet dark grey sidewalk. (C) As B, but here both asphalt surfaces are dry. (D) A dry patchy asphalt road with four different surface characteristics: rr: rough and reddish, rw: rough and white, rg: rough and grey, sb: shiny and black.

Figure 12 shows the reflection-polarization patterns of four different asphalt surfaces under overcast skies. In Figure 12A a wet asphalt with two different white-black chequered patterns is seen. It is clearly visible that the white/black areas of the asphalt reflect light with low/high degrees of polarization *p*, and the direction of polarization of reflected light is everywhere horizontal, because the incident light comes from above (sky), and thus the average plane of reflection is vertical. In Figure 12B a wet light grey asphalt road with a wet dark grey sidewalk are seen. Again, we observe that the darker asphalt sidewalk polarizes the reflected light more strongly than the brighter asphalt road, and both asphalt surfaces reflect horizontally polarized light. Similar reflection-polarization characteristics are seen in

Figure 12C, when both asphalt surfaces are dry, but then the differences in p are smaller between the road and the sidewalk. In Figure 12D a dry patchy asphalt road with four different surface features is shown. The p-pattern shows that the rough surface areas possess a lower polarizing capability than the darker ones. On the other hand, all asphalt patches with various surface characteristics reflect horizontally polarized light, because they are illuminated by light from above (overcast sky). Figure 12D demonstrates well that a patchy asphalt road with heterogeneous surface roughness, brightness and colour possesses a patchy p-pattern, but a homogeneous α-pattern when illuminated only by light from the sky.

Chapter 4

DISCUSSION

4.1. WHEN DO ASPHALT SURFACES REFLECT HIGHLY AND HORIZONTALLYPOLARIZED LIGHT?

On the basis of our quantitative imaging polarimetric measurements we can establish the fundamental polarization characteristics of light reflected from asphalt surfaces as functions of the illumination conditions and surface features. Figure 13 summarizes qualitatively the directions of polarization of light reflected from a sunlit dry asphalt road as a function of the solar azimuth direction relative to the road line. The direction of polarization of asphalt-reflected light is always perpendicular to the plane of reflection determined by the observer (polarimeter), the point observed and the sun (or full moon at night). If the observer is facing the sun, the reflection plane of sunlight is exactly or nearly vertical, thus the direction of polarization of asphalt-reflected light is exactly or nearly horizontal. The same is true when the observer is facing toward the antisolar meridian. Hence, from both directions of view (solar and antisolar meridians) sunlit asphalt surfaces can be attractive to positively polarotactic aquatic insects. If the sun is shining from left/right, the reflection plane of sunlight is tilted to left/right from the vertical, thus the direction of polarization of asphalt-reflected light is tilted to right/left relative to the vertical (or to left/right from the horizontal). Similar reflection-polarization characteristics of sunlit black burnt-up stubble-fields have been measured by Kriska *et al*. (2006b).

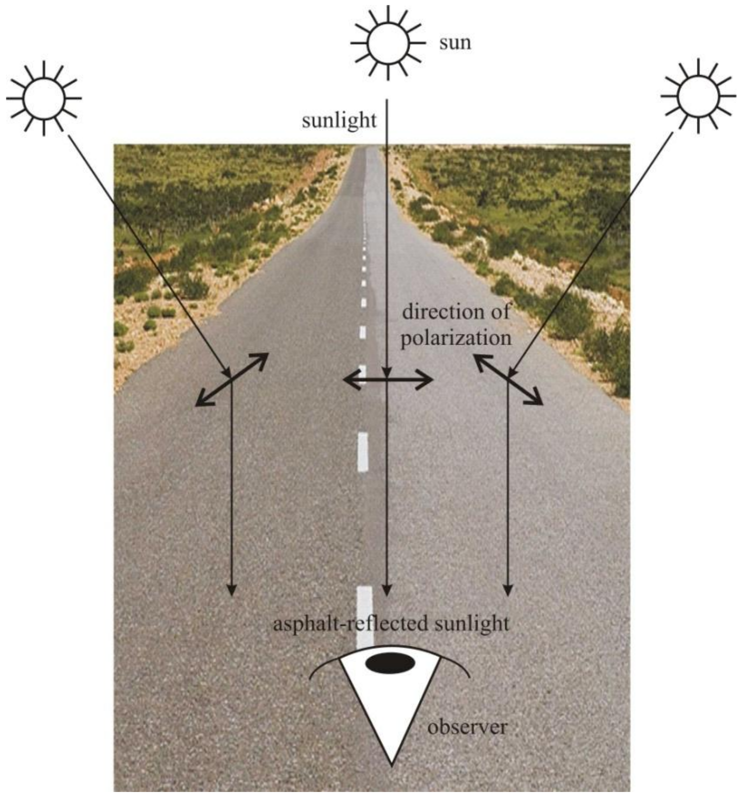

Figure 13. Schematic representation of the directions of polarization (double-headed arrows) of light reflected from a sunlit dry asphalt road for three different solar directions.

Figure 14 shows qualitatively the directions of polarization of skylight/sunlight reflected from shady/sunlit regions of a dry asphalt road. As seen above, the direction of polarization of asphalt-reflected sunlight is usually tilted relative to the horizontal road surface, because it is always perpendicular to the plane of reflection, which is generally oblique. On the other hand, if the road is shady, that is illuminated by skylight only, the asphalt-reflected skylight is always horizontally polarized. Then light from the sky comes from all possible directions from above, and due to symmetry, the average incident direction of skylight is vertical. Thus the average plane of reflection is vertical, consequently, the average direction of polarization of asphalt-reflected skylight is horizontal. Thus, shady asphalt surfaces can always be attractive to polarotactic water insects.

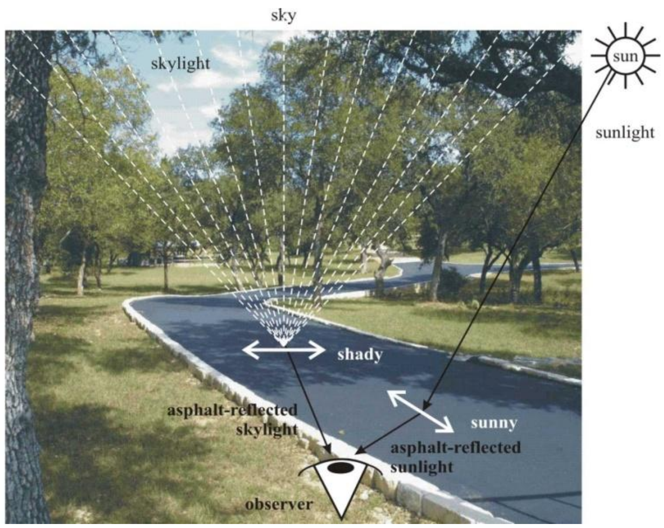

Figure 14. Schematic representation of the directions of polarization (double-headed arrows) of skylight/sunlight reflected from shady/sunlit regions of a dry asphalt road.

Hence, under certain illumination conditions and directions of view, asphalt roads reflect exactly or nearly horizontally polarized light with higher or lower degrees of polarization. This asphalt-reflected sunlight/skylight can be distracting or even blinding for car or van drivers. If the bright asphalt-reflected light is horizontally polarized, then it can be partially filtered by polarized sunglasses with vertical transmission direction. This is shown in Figures 15 and 16. If sunglasses are rotated to and fro in front of our eyes when we look at the sky (or an asphalt road), the firmament (or the road) becomes periodically brighter and darker (Figure 15), because the partially linearly polarized skylight (or asphalt-reflected light) is periodically more or less blocked by the polarizing filter of the sunglasses. Direct sunlight is unpolarized, but after reflection from a horizontal asphalt surface it can become partially horizontally polarized. Polarized sunglasses with vertical transmission axis transmit only the vertically polarized component of direct sunlight, thus reducing its intensity to half. The same is true for the asphalt-reflected light, but its transmitted intensity is much more reduced, because its vertically polarized component is much smaller than that of sunlight. Note that this filtering of the asphalt-reflected light can function only under such special illumination conditions and viewing directions (see above), if the reflected light is exactly or nearly horizontally polarized. Therefore polarized sunglasses do not always function perfectly. Regardless, sunglasses are worth wearing because they also reduce the usually horizontally polarized glitter of water surfaces (Gál *et al*., 2001a; Horváth and Varjú, 2004).

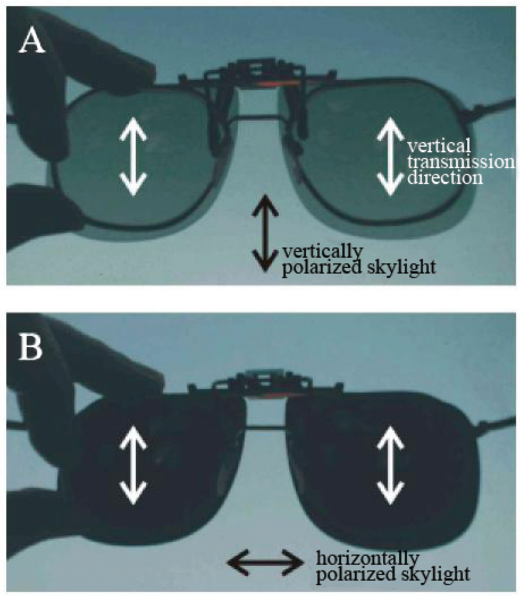

Figure 15. Demonstration of the functioning of a polarizer sunglass. White double-headed arrows show the direction of the transmission axis of the linear polarizer, while black arrows represent the direction of polarization of skylight. (A) If the direction of polarization of skylight is parallel to the transmission direction of the polarizer, skylight is transmitted through the polarizer sunglass, thus the sky looks bright. (B) If the direction of polarization of skylight is perpendicular to the transmission direction of the polarizer, skylight is wiped out by the polarizer sunglass, thus the sky looks dark.

We have seen that the rougher and/or brighter an asphalt surface, the lower the degree of polarization of asphalt-reflected light. Rough surfaces reflect light diffusely, that is in all possible directions, resulting in all possible directions of polarization being always perpendicular to the actual plane of reflection. This phenomenon causes depolarization, i.e. reduction of the net degree of polarization p of reflected light. On the other hand, in a given part of the spectrum (at a given wavelength of light) the larger the intensity of reflected light, the lower its p. This phenomenon is called the

Umow effect (Umow, 1905; Können, 1985; Horváth and Varjú, 2004). The direct consequence of the Umow effect is that darker/brighter asphalt surfaces reflect light with higher/lower degrees of polarization.

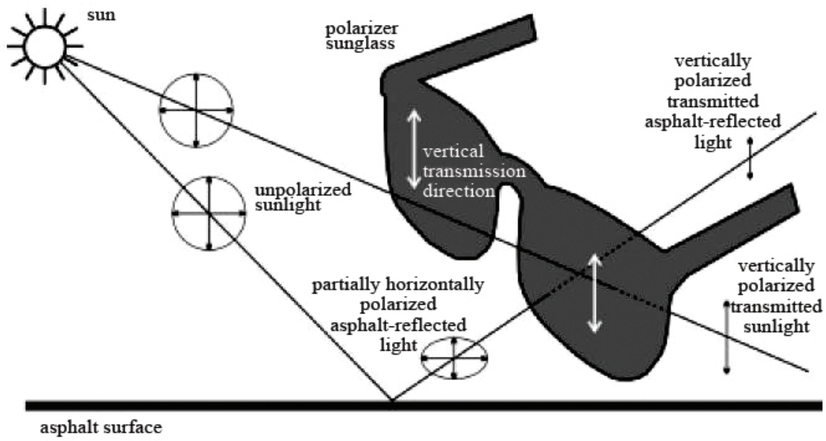

Figure 16. Direct sunlight is unpolarized, but after reflection from a horizontal asphalt surface it can become partially horizontally polarized. A polarizer sunglass with vertical transmission axis transmits only the vertically polarized component of direct sunlight, thus reducing its intensity to half. The same is true for the partially horizontally polarized asphalt-reflected light, but its transmitted intensity is much more reduced, because its vertically polarized component is much smaller than that of sunlight.

4.2. Reducing the Polarized Light Pollution of Asphalt Surfaces

An understanding of the above-mentioned reflection-polarization phenomena can be used to reduce the polarized light pollution of asphalt surfaces near aquatic habitats that host polarotactic insects. The asphalt surface must be prepared in such a way that its surface does become rough and bright. The simplest methods of preparation should be:

- The asphalt surface can be covered by small-sized white gravel. The gravel reflects light diffusely, which results in depolarization. This depolarization is further strengthened by the whiteness of the gravel due to the Umow effect.

- White stripes can be painted onto the asphalt surface. These white stripes depolarize strongly the reflected light because of the Umow effect.

Figure 17 demonstrates an easy way to accomplish a reduction of the polarized light pollution of smooth (shiny) dark (black) asphalt surfaces: covering the asphalt surface with small-sized white gravel.

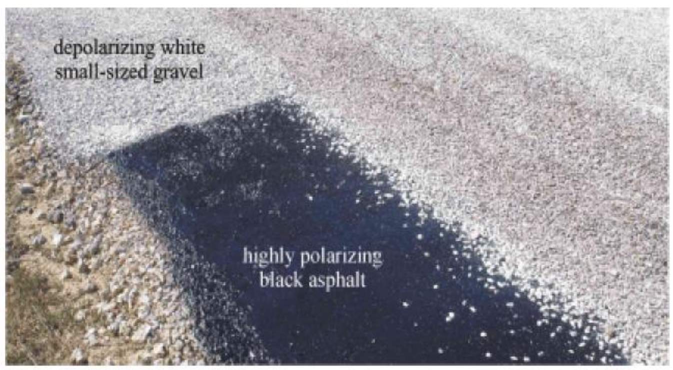

Figure 17. Shiny black horizontal asphalt surfaces are highly and horizontally polarizing, thus they are strong sources of polarized light pollution. This can be reduced or even eliminated, if the asphalt is covered by small-sized white gravel, which depolarizes light due to diffuse reflection (roughness) and the Umow effect (whiteness).

Choice experiments performed in the field showed that if polarotactic insects can choose between a water surface and an artificial surface reflecting highly and horizontally polarized light, the insects will prefer the latter (Horváth and Varjú, 2004). But what is the physical/optical reason for this maladaptive preference? Figure 18 helps explain. The amount of light coming from a water body is usually not negligible relative to that reflected from the water surface. In this case the net polarization of light returned by water is governed by the polarization characteristics of two components: (1) the partially horizontally polarized light reflected from the water surface, and (2) the partially vertically polarized refracted light coming from the water. If, in a given part of the spectrum, the intensity of the first component is larger/smaller than that of the second one, then the water-returned light is partially horizontally/vertically polarized; while if the intensities of both components are equal, the water returns unpolarized light. Consequently, the reflection-polarization characteristics of water bodies strongly depends on the spectrum of light backscattered by the particles suspended in water and of the light reflected by the bottom of water. Dark-looking waters reflect typically highly and horizontally polarized light at the Brewster angle in both the ultraviolet (UV) and visible parts of the spectrum. Bright-looking waters generally return weakly and not always horizontally polarized light in the long-wavelength (red, green) parts of the spectrum, and they reflect highly and horizontally polarized light only in the blue and UV spectral ranges (Horváth and Varjú, 2004). On the other hand, the material of asphalt completely absorbs the 2nd componet of light in Figure 18, thus the reflection-polarization of asphalt-reflected light is determined exclusively by the 1st component, resulting in always very high degrees of polarization ($p \approx$ 100%) with directions of polarization perpendicular to the plane of reflection at the Brewster angle. Shady, dark grey or black asphalt surfaces reflect always highly and horizontally polarized light being very attractive to water-seeking positively polarotactic aquatic insects, while brighter waters reflect weakly and/or not always horizontally polarized light being weakly attractive or even unattractive to these insects. Consequently, polarotactic insects prefer shady, dark asphalt surfaces against brighter water surfaces.

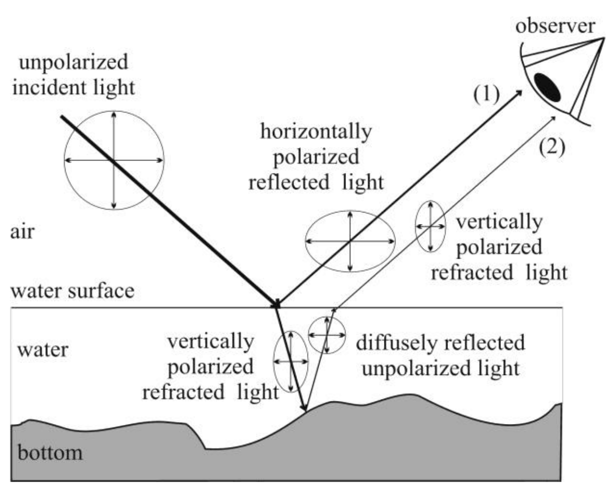

Figure 18. Polarization of light returned from a body of water for unpolarized incident light. The returned light has two components: (1) the partially horizontally polarized light reflected from the water surface, and (2) the partially

vertically polarized refracted light coming from the water. The ellipses and circles with vertical and horizontal double-headed arrows symbolize the "linear polarization ellipse" of light.

Chapter 5

CONCLUSIONS

In summary, we make the following conclusions based on the measurements of polarized light reflected from asphalt surfaces:

(1) The direction of polarization of light reflected from rough sunlit asphalt surfaces is always perpendicular to the plane of reflection/scattering determined by the sun, the observer and the point observed. Since this plane is usually tilted relative to the horizontal asphalt surface, the direction of polarization of light reflected/scattered (returned) by sunlit asphalt surface is generally oblique with respect to the surface. The light returned by sunlit asphalt is (exactly or nearly) horizontally polarized only if the asphalt is viewed towards the solar or antisolar meridian.

(2) The direction of polarization of light reflected from shady asphalt surfaces (illuminated by skylight only) is always (exactly or nearly) horizontally polarized.

(3) The darker/brighter an asphalt surface, the higher/lower the degree of polarization of asphalt-reflected light.

(4) The rougher/smoother an asphalt surface, the lower/higher the degree of polarization of asphalt-reflected light.

(5) The degree of polarization of light reflected from wet asphalt is higher than that reflected from dry one.

(6) If an asphalt surface reflects highly and (exactly or nearly) horizontally polarized light, it can deceive and attract positively polarotactic aquatic insects. These insects perform typical water-specific reproductive behaviour above the asphalt, and the females may lay their eggs onto the asphalt. If polarotactic aquatic insects

are confronted with a highly and horizontally polarizing asphalt surface placed in the vicinity of a water body, they choose the asphalt, because the asphalt-reflected light acts as a supernormal optical stimulus. Since the eggs laid onto asphalt inevitably perish, highly and horizontally polarizing asphalt surfaces can be ecological traps for polarotactic insects. This phenomenon is a typical and well-documented type of polarized light pollution.

(7) The polarized light pollution of asphalt surfaces can be reduced or even eliminated by making the asphalt rough (matte) and bright (or white-striated). Rough asphalt surfaces reflect/scatter light diffusely, and bright/white-striated asphalt surfaces reflect only weakly polarized or unpolarized light. Both treatments ensure that the degree of polarization of asphalt-reflected light can be reduced below the threshold of polarization sensitivity of polarotactic aquatic insects. If a shiny dark asphalt surface is covered by small-sized white gravel, or painted by matte white stripes, the polarized light pollution will be minimal. In areas with gravel roads the change of gravel to the more insect-attracting asphalt should, if possible, be avoided.

(8) We propose to use these remedies at asphalt roads running near the emergence sites of endangered aquatic insects, especially in the vicinity of wetlands, rivers and lakes.

(9) Conservation biologists and asphalt road planners should pay more attention to the reflection-polarization characteristics of asphalt surfaces because of their demonstrated polarized light pollution dangering polarotactic aquatic insects.

ACKNOWLEDGMENTS

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