Fédération S.E.P.A.N.S.O. LANDES
Société pour l'Etude, la Protection et l'Aménagement de la Nature dans le Sud-Ouest (Landes)
1581 route de Cazordite, 40300 CAGNOTTE

De la Nature et des Hommes

www.sepanso40.fr

Cagnotte le 12 novembre 2021

Monsieur Christian Lecaillon
Commissaire enquêteur
c/o C.C. MACS
c/o C.C. SEIGNANX

Transmission électronique : projet.photovoltaique.bedorede@cc-macs.org

Objet : Enquête publique relative au projet de centrale photovoltaïque flottante du lac de Bédorède sur les territoires des communes de Biarrotte et Saint-Laurent de Gosse.

Monsieur le Commissaire enquêteur,

Il y avait bien longtemps que nous n'avions pas vu de projet de centrale photovoltaïque sur une étendue d'eau. Sauf erreur de ma part, le seul qui ait eu lieu dans les Landes concernait un projet dans la commune de Duhort-Bachen (Janvier 2012). Nous savions toutefois que de nouveaux projets étaient en gestation sur des lacs de gravière. Nous avions vu l'article publié par Sud-Ouest le 07/10/2021 : *« Du photovoltaïque sur l'eau en Béarn – pour préserver les terres agricoles, la Chambre régionale d'agriculture soutient des solutions innovantes, comme le photovoltaïque flottant... »*. Dans un tel contexte, la SEPANSO qui a dénoncé en leur temps les projets de barrages (Aire-sur-Adour, Renung...) dans les thalwegs puisqu'ils noyaient des écosystèmes où prospéraient diverses espèces protégées, logiquement s'est intéressée au dossier qui vous a été confié par la présidente du Tribunal administratif de Pau.

S'il est facile d'accéder au dossier sur le site de la Communauté de communes Maremne-Adour-Côte-Sud, il n'en va pas de même sur le site de la Communauté de communes du Seignanx où on ne trouve apparemment que l'avis de la présente enquête.

J'ai donc l'honneur de vous adresser les observations de la Fédération SEPANSO Landes.

1 – Courrier du Président du Conseil départemental en date du 21 juillet 2021

Dans sa réponse Xavier Fortinon fait référence au courrier du 13 avril 2021qui ne figure pas dans le dossier mis à disposition du public. Le « MECDU » étant une procédure qui permet de garantir la prise en compte du projet par les documents d'urbanisme, il convient de s'assurer que la réponse positive repose sur une information satisfaisante, c'est-à-dire complète, du Conseil Départemental. Dans cette réponse il est rappelé que *« le département des Landes s'est engagé en faveur de la réduction des émissions de gaz à effet de serre... »*. La SEPANSO quant à elle rappelle que « le département des Landes s'est également à préserver la biodiversité... ». Il est donc indispensable de vérifier que le porter à connaissance adressé au département comprenait bien toutes les informations utiles sur la biodiversité dans l'espace concerné par le projet.

2 – Courrier de la Direction départementale des territoires et de la mer (Service aménagement et risques) en date du 04 août 2021

Ce courrier est intéressant, malheureusement des passages entiers sont caviardés. Cette censure semble regrettable car un nombre important de paragraphes sont incompréhensibles.
Cette production « édulcorée », sensée éclairer le public, montre toutefois que plusieurs irrégularités sont bien identifiées par l'administration. Habituée aux mécanismes de dérogations et régularisations, les deux mamelles de l'administration, la SEPANSO souhaite savoir, avant toutes choses, si toutes les réglementations sont respectée à l'heure actuelle.

3 – Avis de la Mission régionale d'autorité environnementale

Cet avis porte également sur la mise en compatibilité des documents d'urbanisme des communes concernées par le projet. Le secteur concerné par le projet est actuellement classé en zone naturelle à protéger (Np), ce qui correspondait aux observations et aux attentes des naturalistes. En effet le milieu d'origine ennoyé a vu le plan d'eau colonisé par différentes espèces ; au bout du compte on a pu considérer qu'un nouvel écosystème s'y est développé d'autant plus important qu'il se trouve sur plusieurs trames vertes. S'agissant d'un site Natura2000, il semble surprenant que la MRAE n'évoque pas la nécessité de la production d'une étude d'incidence du projet obligatoire selon la Directive Habitats (92/43/CEE du Conseil du 21 mai 1992)
https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000000339498/

4 – Avis du Syndicat mixte du SCoT du Pays Basque et du Seignanx

Cet avis est intéressant même si nous ne savons pas quel dossier avait été mis à la disposition des membres du Conseil syndical si en amont de la décision 2021-32.
Si les élus ont considéré que le projet est d'intérêt général en s'inscrivant dans la Loi d'orientation sur les énergies de juillet 2005, on se doit d'observer que ces élus n'ont pas fait référence à la Loi pour la reconquête de la biodiversité, de la nature et des paysages promulguée le 9 août 2016.
https://www.ecologie.gouv.fr/loi-reconquete-biodiversite-nature-et-des-paysages
L'avis comprend toutefois un paragraphe important : *« Les centrales photovoltaïques flottantes sont peu présentes en France ; en ce sens, le projet est pionnier mais ne permet pas de disposer de retour d'expérience, notamment sur l'impact environnement. ».* Les élus ont été embarrassés puisqu'ils écrivent : « Le projet proposé permet de renforcer l'offre d'ENR du territoire. L'impact sur le milieu naturel est globalement faible, bien que certains enjeux soient jugés potentiellement forts, ou méconnus dû à l'absence de recul sur ce type d'installation. Ce dernier point doit être pris en compte, et un suivi permettra de s'assurer de l'impact réel du projet sur les milieux naturels et la biodiversité.
Ils ont préféré la transition énergétique à la transition écologique !
La SEPANSO va apporter quelques données déjà utilisées lors d'autres enquêtes publiques concernant des projets photovoltaïques en zone humide pour contester ce choix.

5 - Déclaration de projet, au titre de l'article L. 300-6 du Code de l'Urbanisme emportant mise en compatibilité des documents d'urbanisme (67 pages) présenté par la Communauté de communes de Maremne-Adour-Côte-Sud et de la Communauté de communes du Seignanx

- La SEPANSO s'étonne que ce document ne fasse pas mention des auteurs et de leurs compétences : « *La présente déclaration de projet s'appuie sur l'étude d'impact du projet de centrale photovoltaïque sur le lac de Bédorède, sur les communes de Sainte-Marie-de-Gosse, appartenant à la Communauté de communes de Maremne-Adour-Côte-Sud (MACS), Saint-Laurent-de-Gosse et Biarrotte, appartenant à la Communauté de Communes de Seignanx. Cette étude d'impact a été réalisée par la société ETEN Environnement, spécialisée dans le secteur de l'environnement. L'étude fait partie de la demande de permis de construire portée par la société « Centrale solaire de Bédorède », société codévelopée par VALECO et ETCHART. »* (Introduction – Page 3)

L'étude d'impact ne figure pas intégralement dans la déclaration de projet, sinon toutes les informations utiles seraient disponibles. Il est choquant de voir les auteurs de la déclaration de projet écrire : *« Les éléments techniques du projet sont présentés dans les* ***volets dédiés de l'étude d'impact jointe au dossier de permis de construire*** *(voir chapitre 2 de l'étude d'impact). Dans un souci de lisibilité et de compréhension du dossier, ils sont repris (en grande partie) ci-après. »* (2.1.4. Page 7). Nous avons donc avec cette dernière phrase la preuve que le dossier est incomplet.

- La SEPANSO s'étonne que les porteurs du projet n'aient pas porter celui-ci à la connaissance des habitants des communes concernées.

- La SEPANSO s'étonne que le document ne mentionne pas explicitement qui sont les propriétaires. La SEPANSO s'étonne surtout que le projet puisse être considéré d'intérêt général alors que les bénéficiaires sont des groupes privés : « Une promesse de bail emphytéotique a été signée entre les propriétaires du terrain (Promettant) et les groupes VALECO et ETCHART (Bénéficiaires) en octobre 2018, conférant ainsi aux Bénéficiaires la maitrise foncière de l'ensemble des parcelles nécessaires au développement du projet photovoltaïque. »
  Nota Bene : propriétaires sans majuscule – Bénéficiaires avec majuscule !

- La SEPANSO est étonnée par les caractéristiques techniques de l'installation, en particulier par le faible nombre d'heures de fonctionnement à pleine puissance (1126 h/an).

- Si nous nous inquiétons à propos de l'impact du projet sur l'étendue en eau en raison de l'absence de production de l'étude d'impact, nous nous inquiétons également sur l'impact du raccordement. Contrairement à ce qui est écrit à la page 10 *(« La procédure en vigueur prévoit l'étude détaillée par le Gestionnaire du Réseau de Distribution du raccordement du parc photovoltaïque une fois le permis de construire obtenu, par l'intermédiaire d'une Proposition Technique et Financière (PTF). Le tracé définitif du câble de raccordement ne sera connu qu'une fois cette étude réalisée. Ainsi, les résultats de cette étude définiront de manière précise la solution et les modalités de raccordement de la centrale solaire du lac de Bédorède* »), le responsable d'un projet d'énergie renouvelable doit présenter l'ensemble des impacts (site + raccordement) ; c'est d'ailleurs ce que la préfecture a admis et impose à tout porteur de projet photovoltaïque. Il est stupéfiant de constater que l'impact des travaux de raccordement pourrait être nul.

- Intérêt général de l'opération (Pages 13 et suivantes). Toute la démonstration repose sur la Loi d'orientation sur les énergies (13/07/2005). A fin de la lecture de cette production, on a l'impression que le Grenelle de l'Environnement n'avait pour objectif que la production d'énergies renouvelables. A l'époque, j'étais administrateur de France Nature Environnement, et je peux vous assurer que la protection de la nature était l'axe fondamental de tous les ateliers ! Les ateliers se contentaient d'examiner les interactions entre activités humaines et nature. La conclusion à la page 16 est dans l'air du temps : il faut générer des bénéfices financiers, peu importent les aménités fournies par les milieux naturels ou semi-naturels.

- La SEPANSO rappelle que cette retenue dans le thalweg a été autorisée pour permettre d'arroser des cultures. Il n'y a aucune donnée sur les variations des niveaux d'eau, alors qu'il s'agit bien d'un critère technique. <u>Pourquoi cette lacune énorme dans ce dossier ?</u>

- Choix du site et analyse des variantes (Page 17 et suivantes). Nous y sommes habitués, mais nous observons une nouvelle fois que le porteur de projet présente des variantes très impactantes pour faire accepter un projet moins impactant, mais impactant tout de même.

- La mise en compatibilité des Plans Locaux d'Urbanisme suppose la transformation d'une zone Np (naturelle à protéger) en une zone NEnR par un simple changement d'écritures du classement et du règlement. Selon le mécanisme Eviter-Réduire-Compenser les porteurs du projet auraient dû normalement expliquer comment ils compensent les impacts de leur projet.

- La mise en compatibilité du SCoT (Page 22). La SEPANSO rappelle comment le SCoT prévoyait la production d'énergies renouvelables : « Le SCoT préconise l'étude et le développement, quand cela est possible, des énergies renouvelables... ». A nouveau, nous tenons à souligner que le projet artificialise un espace remarquable. A la différence des promoteurs du projet, la SEPANSO estime qu'il faut conserver l'état naturel du site. Nous contestons la conclusion : *« Le projet de centrale photovoltaïque est donc compatible et répond aux enjeux fixés par le SCOT de l'agglomération de Bayonne et du Sud des Landes. »*

- En conséquence nous contestons la pertinence des écritures de la pages 24 et suivantes relatives aux modifications des documents des communes concernées par le projet.

- Évaluation environnementale (Page 35 et suivantes). L'artificialisation du lac de Bédorède correspondrait à une modification de l'écosystème et à une modification paysagère. L'affirmation de la prise en compte des contraintes Natura2000 est fausse : il faut impérativement réaliser une étude d'incidence, laquelle fait manifestement défaut. La référence au SRADDET n'est pas plus pertinente puisque l'atteinte à un milieu ne saurait s'inscrire dans une stratégie de développement durable.

- A propos de l'étude d'impacts –. Il semble pour le moins étonnant que ce qui a été écrit et diffusé à maintes reprises ne soit toujours pas intégré par ce Bureau d'études ! Ainsi la SEPANSO avait alerté tous les décideurs à propos de l'impact potentiel sur la reproduction des insectes aquatiques dont le rôle dans la chaîne alimentaire est au programme de l'éducation nationale obligatoire. Lorsqu'on dit qu'on ne connaît pas vraiment tous les impacts du photovoltaïques flottant, la SEPANSO est d'accord, mais pour commencer il faudrait déjà utiliser les études existantes ! En évitant de s'intéresser à cette problématique cela permet d'affirmer qu'il y a un manque de données environnementales...

Panneaux photovoltaïques : impact potentiel sur la reproduction des insectes aquatiques
Comme la plupart des surfaces réfléchissantes sombres, artificielles ou naturelles, telles que la surface des plans d'eau, les panneaux photovoltaïques ont la faculté de renvoyer une lumière polarisée.
Or plus de 300 espèces d'insectes utilisent la lumière polarisée pour repérer les lacs et les rivières. Ceci pourrait donc avoir un effet fâcheux sur la reproduction de certains insectes qui affectionnent les zones humides ou les plans d'eau voire s'y reproduisent. Cela peut contribuer à augmenter le nombre des attaques de prédateurs et/ou à faire chuter la reproduction des insectes aquatiques.
Une étude révélée par la Commission Européenne montre que ces surfaces de panneaux solaires polarisent la lumière encore davantage que la surface de l'eau et sont très attractifs pour certains insectes tels que les Éphéméroptères, les Trichoptères, les Diptères Dolichopodidés et Tabanidés qui ont tendance à s'y précipiter.
Toutefois, les cellules solaires encadrées de blanc ou les panneaux quadrillés par des rubans blancs réfléchissent plus faiblement la lumière et sont moins susceptibles d'attirer les insectes. Par exemple : on observe 6,9 fois plus d'atterrissages d'Ephémères sur des panneaux noirs que s'ils sont bordés de blanc, on totalise 16,7 fois plus de d'Éphémères, 26,5 fois plus de Trichoptères et 10,3 fois plus de Dolichopodidés capturés par une surface non quadrillée que par une surface quadrillée. Mais un tel cloisonnement des panneaux va nécessairement diminuer leur capacité à produire de l'électricité.
Bien que cette étude, qui aurait besoin d'être complétée, ne permette pas de connaître l'importance de l'impact des panneaux solaires sur la reproduction ou les prédations, il y a lieu d'être très inquiet pour la biodiversité dans la mesure où les installations de panneaux photovoltaïques se multiplient.
Source : Horváth, G., Blahó, M., Egri, A. *et al.* (2010) Reducing the Maladaptive Attractiveness of Solar Panels to Polarotactic Insects. *Conservation Biology.* 24(6):1644-1653. Article « Science for Environment Policy » (3 février 2011)
Article publié dans SUD-OUEST NATURE n° 151 – février 2011

- Toujours à propos de l'étude d'impact - Une nouvelle fois la SEPANSO n'apprécie pas les évaluations d'ETEN qui minore singulièrement les impacts du projet. L'évaluation des effets sur prévisibles sur le paysage (page 49) en sont la preuve flagrante : ce site est un lieu où des citoyens examinent la nature et on ne peut pas estimer que l'impact « Paysage culturel » sera « nul ». A la limite on pourrait considérer qu'il y aura un transfert de la culture « biodiversité » à la culture « génie industriel ». Nota Bene : il est surprenant de voir utiliser l'adjectif « méconnu » pour apprécier l'importance des impacts (« méconnu = qui n'est pas apprécié selon son mérite » ; il aurait sans doute mieux valu utiliser « inconnu ».

- Mesures d'évitement : La SEPANSO estime qu'elles sont fatalement insuffisantes puisque des paramètres importants sont méconnus.

Conclusions :

Le dossier est incomplet et le public n'est donc pas en mesure d'apprécier si le projet est d'intérêt général. Il est regrettable que le porteur du projet n'ait pas pris la peine de fournir l'étude d'impact obligatoire (procédure d'autorisation environnementale pour respecter l'article L. 411-1 du code de l'environnement). Nota Bene : il convient impérativement de maintenir dans un état de conservation favorable les populations d'espèces protégées présentes sur le site. Le projet est litigieux dans la mesure où il est en contradiction avec le SCoT et ne répond à aucune raison impérative d'intérêt public majeur.

Les porteurs de ce projet surprennent les adhérents de la SEPANSO qui connaissent et apprécient les lieux où il est projet d'implante du solaire photovoltaïque. Il semble étonnant que la collectivité territoriale puisse participer à hauteur de 1 million d'euros alors que le projet est porté par un consortium privé. Un sentier de randonnée longe le lac et des panneaux attirent l'attention du public sur le caractère sensible de l'environnement.

Nous avons apprécié la contribution de Monsieur Nicolas Betbeder qui n'est pas adhérent de la SEPANSO, mais conteste lui aussi l'intérêt du projet.

En vous remerciant pour l'attention portée à nos observations, veuillez agréer, Monsieur le Commissaire enquêteur, l'expression de notre considération distinguée.

Georges CINGAL
Président Fédération SEPANSO Landes
Secrétaire Général Fédération SEPANSO Aquitaine
1581 route de Cazordite - 40300 Cagnotte
+33 5 58 73 14 53
Georges.cingal@orange.fr
http://www.sepanso40.fr

Pièces jointes :
Revue Horvath & al 2009
Revue Horvath & al 2010

Polarized light pollution: a new kind of ecological photopollution

Gábor Horváth[1], György Kriska[2], Péter Malik[1], and Bruce Robertson[3*]

The alteration of natural cycles of light and dark by artificial light sources has deleterious impacts on animals and ecosystems. Many animals can also exploit a unique characteristic of light – its direction of polarization – as a source of information. We introduce the term "polarized light pollution" (PLP) to focus attention on the ecological consequences of light that has been polarized through interaction with human-made objects. Unnatural polarized light sources can trigger maladaptive behaviors in polarization-sensitive taxa and alter ecological interactions. PLP is an increasingly common byproduct of human technology, and mitigating its effects through selective use of building materials is a realistic solution. Our understanding of how most species use polarization vision is limited, but the capacity of PLP to drastically increase mortality and reproductive failure in animal populations suggests that PLP should become a focus for conservation biologists and resource managers alike.

Front Ecol Environ 2009; 7(6): 317–325, doi:10.1890/080129 (published online 7 Jan 2009)

The term "ecological light pollution" (ELP) has been coined to describe all kinds of photopollution that disrupt the natural patterns of light and dark experienced by organisms in ecosystems (Longcore and Rich 2004). ELP includes direct glare, chronically increased illumination, and temporary, unexpected fluctuations of light emitted from lighted structures (eg buildings, towers, bridges) and vehicles. Artificial lights can attract or repulse organisms, leading to increased predation, maladaptive migration behavior, selection of inferior nest sites or mates, collisions with artificial structures, altered competition for resources, reduced time available for foraging, and disrupted predator–prey relationships that can, in turn, alter community structure (reviewed in Longcore and Rich 2004). This positive or negative phototaxis is elicited by the intensity and/or color of artificial light, which has been considered as the major visual phenomenon underlying ELP. Yet other characteristics of light are visible too, and are used as behavioral cues by animals.

In particular, it has become clear that many animals are capable of perceiving the polarization of light and use it as a rich source of information (eg von Frisch 1967; Lythgoe and Hemmings 1967; Schwind 1985, 1991, 1995; Danthanarayana and Dashper 1986; Shashar *et al.* 1998; Wildermuth 1998; Marshall *et al.* 1999; Novales Flamarique and Browman 2001; Wehner 2001; Labhart and Meyer 2002; Dacke *et al.* 2003; Horváth and Varjú 2004; Waterman 2006; Wehner and Labhart 2006; Henze and Labhart 2007). In this work, we introduce the term "polarized light pollution" (PLP) as a new kind of ecological light pollution. PLP refers predominantly to highly and horizontally polarized light reflected from artificial surfaces, which alters the naturally occurring patterns of polarized light experienced by organisms in ecosystems. We first discuss known and potential sources of naturally occurring and artificially produced polarized light, and contrast the scale and timing of PLP with that of ELP. We then review our current understanding of the influence of PLP on the behavior of polarization-sensitive organisms and their ecological interactions and communities.

In a nutshell:

- Polarized light pollution includes light that has undergone linear polarization by reflecting off smooth, dark buildings, or other human-made objects, or by scattering in the atmosphere or hydrosphere at unnatural times or locations
- Artificial polarizers can serve as ecological traps that threaten populations of polarization-sensitive species
- Artificial polarized light can disrupt the predatory relationships between species maintained by naturally occurring patterns of polarized light, and has the potential to alter community structure, diversity, and dynamics

[1]*Biooptics Laboratory, Department of Biological Physics, Physical Institute, Eötvös University, Budapest, Hungary;* [2]*Group for Methodology in Biology Teaching, Biological Institute, Eötvös University, Budapest, Hungary;* [3]*WK Kellogg Biological Station, Michigan State University, Hickory Corners, MI *(roberba1 @msu.edu)*

Natural and artificial sources of polarized light

Ordinary white light (eg sunlight, consisting of electromagnetic waves vibrating at all possible planes perpendicular to the direction of propagation) is unpolarized, but light is totally linearly polarized when its waves oscillate only in a single plane. Partially linearly polarized light with a given wavelength is commonly characterized by three parameters: the intensity I, the degree of linear polarization p, and the angle of polarization α, which

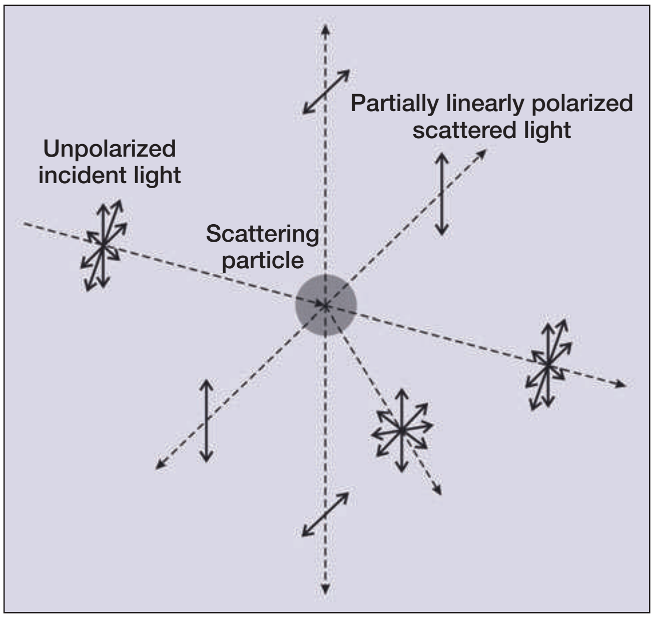

Figure 1. *After scattering on a particle, unpolarized light – whose electric field vector (double-headed arrows) with the same length vibrates in all possible directions perpendicular to the direction of propagation (dashed arrows) – becomes partially linearly polarized. Its electric field vector is shorter in the plane of scattering than that perpendicular to this plane.*

describes the alignment of the plane of oscillation of the electric field vector relative to a given reference (eg vertical) direction. *I* is proportional to the number of photons incident perpendicularly to a unit surface per a unit time interval; *p* is the percentage of photons vibrating in the plane of polarization. In the natural, optical environment, partially linearly polarized light is abundant; this arises from two primary sources: (1) the scattering of sunlight and moonlight within the atmosphere and hydrosphere (Figure 1), and (2) the reflection of light off the surface of water bodies and other non-metallic surfaces (eg rocks, soil, vegetation; Figure 2). We will focus entirely on partially linearly polarized light, the most common naturally occurring form of light polarization on Earth.

Solar radiation is unpolarized before entering Earth's atmosphere, but is partially linearly polarized through interactions with atmospheric gases, aerosols, water droplets, and ice crystals (Coulson 1988; Figure 1). The result is a characteristic celestial polarization pattern with skylight usually polarized perpendicular to the plane of scattering (defined by the observer, the celestial point observed, and the position of the Sun or Moon), and maximum *p* is generally found at 90° from the Sun or Moon (Können 1985). Patterns of polarized light in the sky provide reliable information about the location of these celestial bodies that animals can use to orient themselves and direct their movements. Aquatic and marine organisms can rely on a similar polarization pattern, produced by the scattering of light in the hydrosphere (Lythgoe and Hemmings 1967; Shashar *et al.* 1998; Marshall *et al.* 1999; Novales Flamarique and Browman 2001; Waterman 2006).

Unpolarized light can also undergo strong polarization by reflection (Figure 2). Water is the primary natural source of horizontal polarization by reflection (Figure 3a), and its depth, turbidity, transparency, surface roughness, substratum composition, and illumination strongly influence the reflection–polarization characteristics of its surface (Horváth and Varjú 2004). In general, the extent to which an object polarizes light depends on the angle of reflection and on the material from which its surface is made, with darker and smoother (shinier) surfaces producing higher *p* (Umow 1905).

Diffuse reflection from rough surfaces in all possible directions results in depolarization (reducing *p*), because the reflected electromagnetic waves vibrate in many planes. The net *p* of light returned by an object is determined by the relative intensities of (1) light reflected from the object's surface and (2) light scattered back from the object's material and refracted at its surface. The first and second components are polarized parallel and perpendicular to the reflecting surface, respectively, and therefore have a mutual, depolarizing effect on one another. If, in a given part of the spectrum, the first component is more/less intense than the second one, the net plane of polarization of returned light is parallel/perpendicular to the reflecting surface. If both components are equally intense, the returned light is unpolarized. When the returned light is polarized parallel to the surface, the more intense the second component, the lower the net *p*. On the other hand, the more/less intense the second component, the

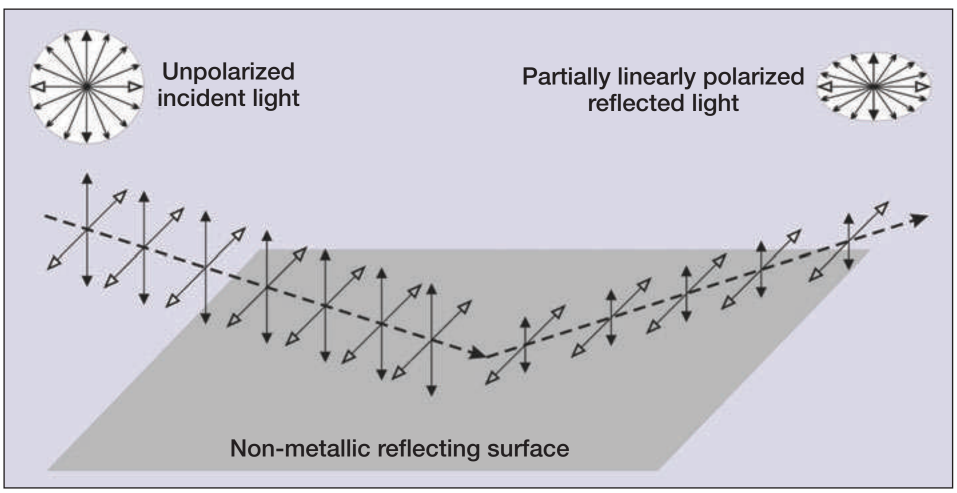

Figure 2. *After reflection from a non-metallic surface, unpolarized light becomes partially linearly polarized. The electric field vector is shorter in the plane of reflection (double-headed arrows with black heads) than in the perpendicular plane (double-headed arrows with open heads).*

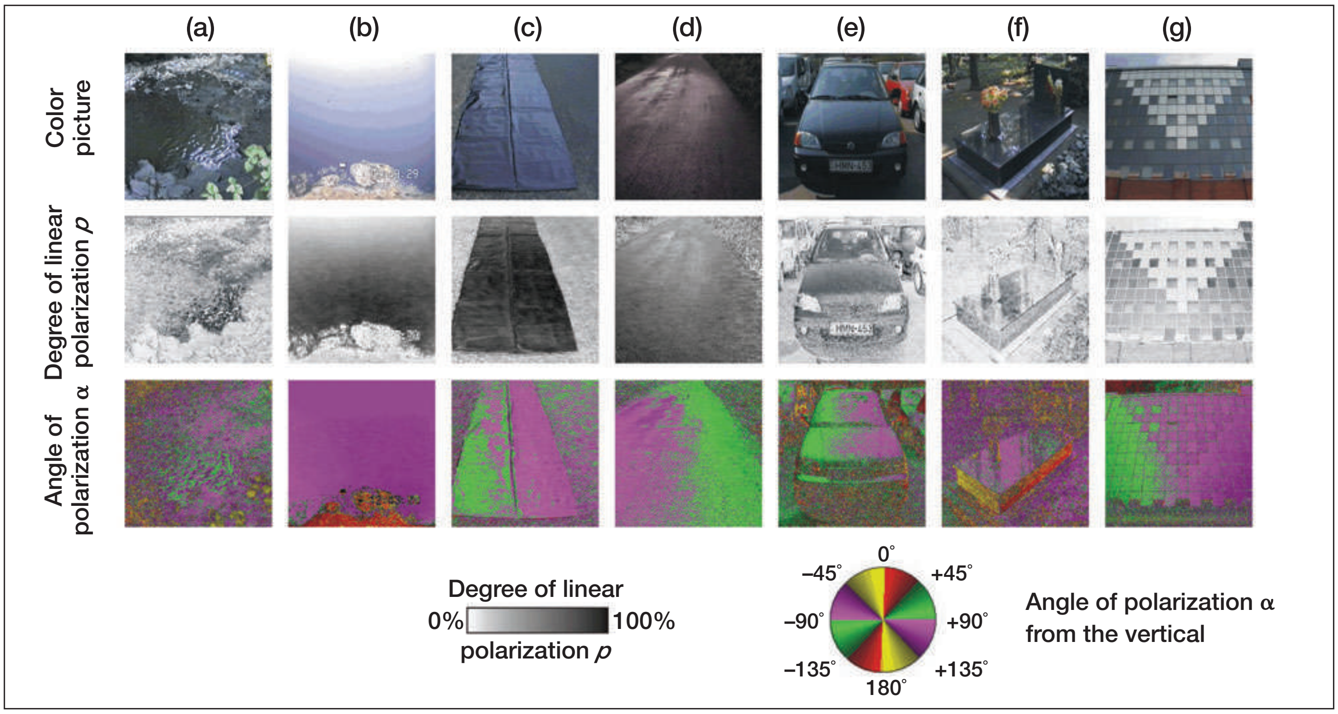

Figure 3. *Color photos, patterns of the degree of linear polarization* p*, and the angle of polarization* α *of a water surface (a) and different artificial surfaces (b–g) causing PLP. (a) Dark water body. (b) Crude oil lake in the desert of Kuwait. (c) Black plastic sheet on an asphalt road. (d) Dry asphalt road. (e) Black car. (f) Polished black gravestone. (g) Windows with gray/black glass ornamentation.* p *is the percentage of photons vibrating in the plane of polarization. Darker gray tones encode higher* p *(white:* p = *0%, black:* p = *100%).* α *is the alignment of the plane of polarization measured clockwise from the vertical. Different* α *values are encoded by different colors and hues (red:* $0° \leq \alpha < +45°$*, green:* $+45° \leq \alpha < +90°$*, violet:* $+90° \leq \alpha < +135°$*, yellow:* $+135° \leq \alpha < +180°$*). At a given color, the hue encodes different angles* α *with a step of* $\Delta\alpha = 1°$*.*

brighter/darker the object. Thus, in a given part of the spectrum, brighter/darker surfaces reflect light with lower/higher *p*. This phenomenon is called the Umow effect (Können 1985).

One of the consequences of this phenomenon is that, in a given spectral range, smooth darker surfaces are more effective at producing PLP than are brighter ones. Hence, there is an inverse correlation between the brightness of a smooth surface and the amount of PLP produced by it. Thus, if a smooth object is bright/dark in the ultraviolet (UV) spectral range, it reflects UV light with low/high *p*. Consequently, brighter UV reflectors are less effective at producing PLP. This is important in light of the widespread UV sensitivity of birds and insects (Schwind 1991, 1995; Tovée 1995). Many aquatic insects that are attracted to horizontally polarized light sources are also attracted to unpolarized UV blacklight (Nowinszky 2003). Therefore, one can decide only with appropriately designed multiple-choice experiments whether it is the UV spectrum or the polarization of light that serves as the attractant signal (eg Schwind 1985, 1991, 1995; Danthanarayana and Dashper 1986; Horváth *et al.* 1998, 2007, 2008; Kriska *et al.* 1998, 2006a, 2007, 2008a; Bernáth *et al.* 2001b; Dacke *et al.* 2003; Horváth and Varjú 2004).

Modern human development has resulted in the introduction of different sources of polarized light pollution to natural habitats, primarily as a byproduct of the human architectural, building, industrial, and agricultural technologies. Many human products – including black plastic sheets (used in agriculture), asphalt roads, oil spills and open-air waste oil reservoirs, dark-colored paintwork (eg of automobiles), black gravestones, and glass panes (Figure 3b–g) – share important physical characteristics of the most common natural polarizer, the surface of dark waters (Figure 3a), and polarize light strongly.

The phenomenon of PLP is global and has increased rapidly over the past several decades, following the rapid spread of urban development, road systems, and industrial agriculture. Although the magnitude and prevalence of PLP have greatly increased with human activity, PLP can also occur naturally (eg ancient asphalt pits). Because ELP results from the incidence of visible light at times and places where it does not occur naturally, ELP is predominantly a night-time phenomenon, affecting nocturnal and crepuscular species. In contrast, PLP can occur during both light and dark cycles in terrestrial environments, and in other permanently dark habitats, as long as both artificial light sources and polarizing substances are present.

Ecological effects of polarized light pollution

Many animals, including birds, reptiles, amphibians, fish, insects, crustaceans (eg crabs and shrimp), and even echinoderms, have amazingly well-tuned polarization

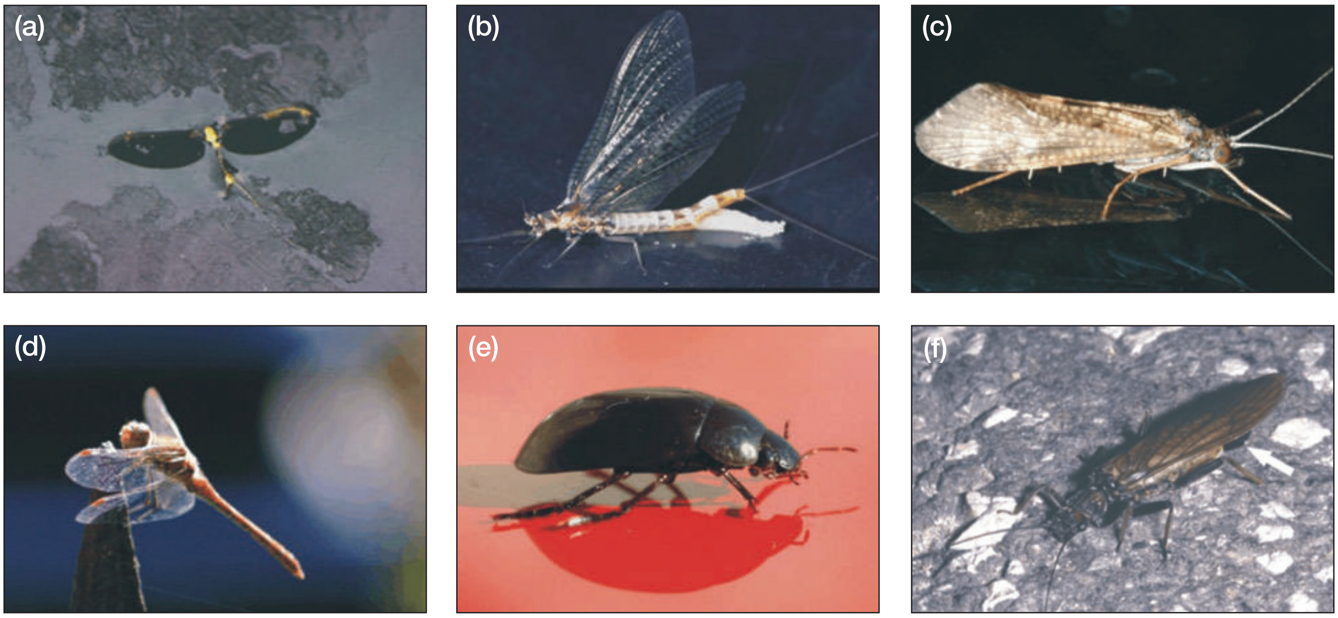

Figure 4. *Polarotactic, water-loving insects attracted to different PLP sources. (a) Mayfly trapped in a waste oil lake in Budapest, Hungary; (b) mayfly laying eggs on a horizontal black plastic sheet; (c) caddisfly on a vertical glass pane (the picture is rotated by 90°); (d) male dragonfly perching above a polished horizontal black tombstone; (e) water beetle on a red car roof; (f) ovipositing stonefly (white arrow: eggs) on a dry asphalt road.*

vision (reviewed in Danthanarayana and Dashper 1986; Schwind 1995; Wehner 2001; Labhart and Meyer 2002; Horváth and Varjú 2004; Waterman 2006; Wehner and Labhart 2006). In this section, we review cases in which anthropogenic sources of polarized light affect the behavior and fitness of polarization-sensitive animals, directly or indirectly, and discuss the potential for PLP to influence ecological interactions with other species.

Habitat selection and oviposition

Polarized light pollution caused by artificial planar surfaces has clear and deleterious impacts on the ability of animals to judge safe and suitable habitats and oviposition sites. In particular, PLP presents severe problems for organisms associated with water bodies. Orientation to horizontally polarized light sources is the primary guidance mechanism used by at least 300 species of dragonflies, mayflies, caddisflies, tabanid flies, diving beetles, water bugs, and other aquatic insects. This is used to search for suitable water bodies to act as feeding/breeding, habitat, and oviposition sites (Schwind 1991; Horváth and Kriska 2008). Because of their strong horizontal polarization signature, artificial polarizing surfaces (eg asphalt, gravestones, cars, plastic sheeting, pools of oil, glass windows) are commonly mistaken for bodies of water (Horváth and Zeil 1996; Kriska *et al.* 1998, 2006a, 2007, 2008a; Horváth *et al.* 2007, 2008). Because the p of light reflected by these surfaces is often higher than that of light reflected by water, artificial polarizers can be even more attractive to positively polarotactic (ie lured to horizontally polarized light) aquatic insects than a water body (Horváth and Zeil 1996; Horváth *et al.* 1998; Kriska *et al.* 1998). They appear as exaggerated water surfaces, and act as supernormal optical stimuli.

The ecological consequences of attraction to these PLP sources vary. Attraction to oil spills and pools typically results in mortality for organisms that touch or land on the surface of the oil and cannot escape. Large numbers of dragonflies, mayflies, caddisflies, water bugs, and water beetles are trapped by waste oil pools and oil spills in spring, summer, and autumn, during their annual swarming and migration (Horváth and Zeil 1996; Bernáth *et al.* 2001a; Figure 4a). Some insect species are attracted to plastic sheeting, which causes them to swarm, land, crawl, copulate, and lay eggs (Figure 4b), while many others (eg aquatic bugs – Heteroptera, and water beetles – Coleoptera) dry out and perish within hours (Bernáth *et al.* 2001b; Kriska *et al.* 2007). Emerging caddisflies (*Hydropsyche pellucidula*) are attracted to the vertical glass surfaces of buildings on river banks (Figure 4c) as a result of their strong, horizontal polarization signature (Kriska *et al.* 2008a; Malik *et al.* 2008; Figure 3g), an effect that is strengthened by building lights after dark. Because they copulate and remain attracted to the glass panes for hours, many individuals become trapped by partly open tiltable windows and perish.

Many aquatic insects experience complete reproductive failure when they lay eggs on artificial polarizers. Dragonflies (Wildermuth 1998; Figure 4d) and mayflies (Figure 4a, b) carry out sexual behaviors and lay eggs on unsuitable surfaces (eg shiny cement floors, black benches, glass panes, black plastic sheets, and horizontal black gravestones) that, like water, reflect horizontally polarized light. Strong polarization patterns also make black or red cars (Figure 3e) attractive to a host of species

(Kriska *et al.* 2006a; Figure 4e). Male dragonflies often perch on car antennas and establish territories on automobile hoods, while females frequently land and lay their eggs on horizontal car surfaces, where they fail to hatch (Wildermuth and Horváth 2005). Polarotactic mayflies and other insects (Figure 4f) commonly swarm above, land/copulate on, and oviposit onto dry asphalt surfaces that reflect horizontally polarized light (Kriska *et al.* 1998; Figure 3d). Attraction to PLP sources is often so great that individuals appear incapable of leaving, a behavior we call the "polarization captivity effect" sensu Eisenbeis (2006), which culminates in the death of the insects as a result of dehydration and exhaustion.

It is not surprising that water-seeking insects use horizontally polarized light to locate water bodies – among the available visual cues, polarization is the most reliable under variable lighting conditions (Schwind 1985; Horváth and Varjú 2004). Certain waterbirds are attracted to pools of oil, in which they drown, and they also try to forage on plastic sheeting laid on the ground, which appears to them as a small body of water (Bernáth *et al.* 2001a). Foraging on this type of inappropriate, artificial habitat wastes time and energy, but landing on artificial reflectors can be lethal for other species.

Obligate waterbirds, such as the ruddy duck (*Oxyura jamaicensis*), common loon (*Gavia immer*), dovekie (*Alle alle*), and brown pelican (*Pelecanus occidentalis*), are occasionally found dead or injured and stranded (unable to take off) in large asphalt parking lots (McIntyre and Barr 1997; Montevecchi and Stenhouse 2002), or on asphalt roads in the desert (Kriska *et al.* 2008b). Strandings commonly take place at night, when bright, downward-facing streetlights are reflected upwards by asphalt surfaces, creating a strong optical signature during a time of day when few cues for locating water bodies are available. Studying the possible role of polarization vision of these waterbirds in water detection is the task of future research.

Foraging ecology

Polarization sensitivity can be used by certain predators to help detect suitable prey. Underwater, both the degree and the direction of polarization created by scattering depend on the position of the Sun or Moon. But when scattered light passes through the transparent body of small aquatic prey animals (eg jellyfish, ctenophores), its polarization signature is altered, increasing the visual contrast of the prey species relative to the background (Lythgoe and Hemmings 1967; Shashar *et al.* 1998): transparent bodies repolarize transmitted, reflected, or refracted light and stand out against a background polarized in a different plane and at a different magnitude. Plankton feeders are adept at detecting zooplankton in the water column that would otherwise be transparent (Novales Flamarque and Browman 2001). In this way, cephalopods, trout, and other aquatic predators can detect the polarization signature of camouflaged and/or distant prey (Shashar *et al.* 1998; Marshall *et al.* 1999; Novales Flamarque and Browman 2001). Longfin squid (*Loligo pealei*) also use polarized light as a hunting cue and will eat clear, polarizing beads in preference to non-polarizing ones (Shashar *et al.* 1998).

Underwater plastic garbage is another source of PLP, and may prompt aquatic organisms into consuming inappropriate and dangerous items. Transparent plastic is an abundant pollutant in marine environments throughout the world (reviewed in Derraik 2002); it alters the polarization of light passing through it, in the same way as small transparent organisms, because its index of refraction is different from that of water. The polarization signature of plastic refuse may also be problematic for sea turtles, since they may also be sensitive to polarized light (C Mora pers comm). Turtles commonly ingest plastic, particularly transparent plastic bags (Gramentz 1988; Bugoni *et al.* 2001), which have a polarization signature similar to that of prey items they commonly target (eg jellyfish, ctenophores). In addition to direct mortality (Duguy *et al.* 1998), sea turtles may experience reduced growth rates, which increases their vulnerability to large predators, and reduced energy reserves and migratory ability, as a consequence of plastic ingestion (McCauley and Bjorndal 1999). Plastic bags may attract sea turtles solely on the basis of their transparency and similarity in shape to jellyfish, yet the role of polarization signals in the interaction between plastic garbage, sea turtles, and other aquatic organisms deserves further study. Polarization vision in piscivorous predators should enhance detection of silvery-colored fish, by breaking their spectral camouflage (Marshall *et al.* 1999). The polarized light signatures of plastic refuse should therefore enhance its attractiveness to a number of polarization-sensitive predators (eg fish, cephalopods, birds; reviewed in Wehner 2001; Horváth and Varjú 2004; Waterman 2006; Wehner and Labhart 2006), making the potential scope of the problem both taxonomically and geographically widespread.

Navigation and orientation

Many taxa (eg birds, reptiles, fish, insects, crustaceans, and echinoderms) use polarized light patterns in the sky or hydrosphere as an orientation cue (reviewed in Danthanarayana and Dashper 1986; Schwind 1995; Wehner 2001; Labhart and Meyer 2002; Horváth and Varjú 2004; Waterman 2006; Wehner and Labhart 2006). Artificial polarized light (eg reflected from glass buildings or scattered in water around fishing boats and undersea research vessels) could therefore disrupt evolved polarization-based navigation and orientation behaviors. Certain bees, crickets, desert ants, and beetles, for instance, use the skylight polarization patterns as a cue for orientation during their dispersal and migration (eg von Frisch 1967; Labhart and Meyer 2002; Dacke *et al.* 2003), yet a wide range of nocturnal insects are attracted to, and "trapped" by, artificial point sources of polarized light (Kovarov and

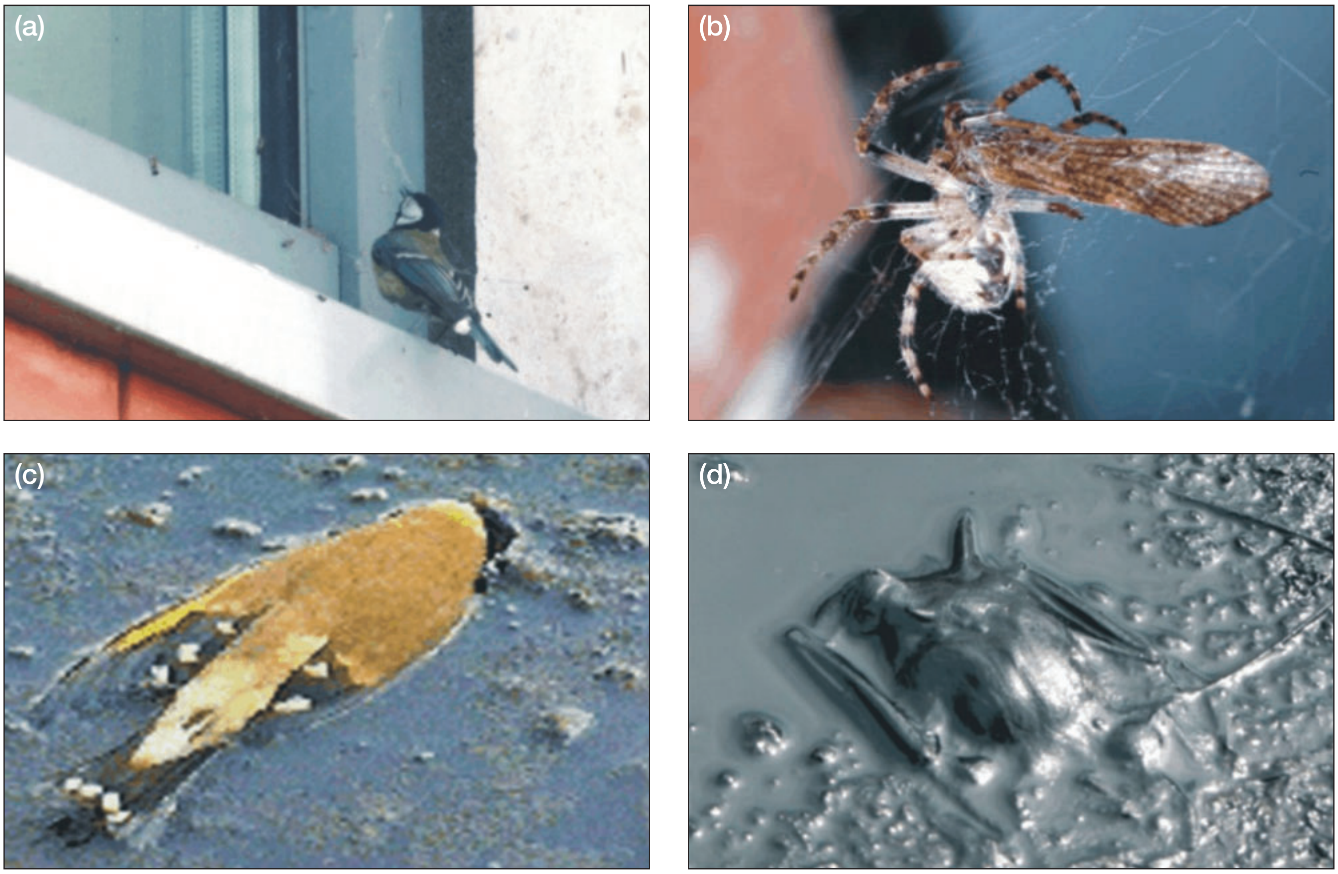

Figure 5. *Predators feeding on polarotactic insects attracted to two PLP sources. (a) A great tit and (b) an orb-weaver spider feeding on caddisflies attracted to vertical glass surfaces; (c) carcasses of a European goldfinch and (d) a bat trapped by a waste oil lake in Budapest, Hungary.*

Monchadskiy 1963; Danthanarayana and Dashper 1986). The maximum *p* of skylight is highly variable, ranging from 15–75% (Coulson 1988), so highly polarizing artificial surfaces (Horváth and Pomozi 1997) that reflect light downwards may easily become supernormal polarization signals to which different species are attracted. Field crickets (*Gryllus campestris*), for example, can orient to degrees of polarization of only 5–7% (Henze and Labhart 2007), while artificial polarizing surfaces may produce a signal as high as 80–95% (Horváth and Varjú 2004). Artificial surface reflections may therefore be confused with natural polarized light produced by scattering in the atmosphere.

Predation

Although the direct effects of PLP on polarotactic organisms are commonly negative, PLP can indirectly benefit species that feed on, or compete with, polarotactic organisms. Anuran amphibians, reptiles, birds, bats, and spiders hunt insects attracted to streetlamps at night (reviewed in Rich and Longcore 2006); this is a well-known, secondary effect of conventional (non-polarized) ecological photopollution. Similarly, wagtails (*Motacilla alba* and M *flava*) readily hunt polarotactic insects attracted to dry asphalt roads and highly polarizing black plastic sheets laid on the ground, which function like a huge bird feeder (Kriska *et al.* 1998; Bernáth *et al.* 2008). Caddisflies attracted to vertical glass surfaces lure diverse predators, including birds, such as European magpies (*Pica pica*), white wagtails (M *alba*), house sparrows (*Passer domesticus*), and great tits (*Parus major*; Horváth and Kriska unpublished data), which systematically hunt and catch the caddisflies that have landed on glass panes or are swarming near windows (Figure 5a). Spiders are also attracted in large numbers to feed on these caddisflies (Figure 5b).

Cascading effects may result if predators, initially benefiting from the abundance of caddisflies attracted to the glass surfaces, become prey themselves. For example, magpies gathering near caddisfly congregations could represent an enhanced predatory risk for the chicks of other bird species that nest in the immediate vicinity of glass buildings, because magpies are nest predators of other, smaller birds (Parker 1984). In this way, the ecological trap for caddisflies could actually trigger a secondary ecological trap for several bird species that prey upon the caddisflies. Spiders attracted to prey upon caddisflies also become prey animals in this altered food web (Figure 5b; Horváth and Kriska unpublished data).

A similar, but more complex food web has been observed by Bernáth *et al.* (2001a) at an open-air waste oil reservoir in Budapest, Hungary. The strongly, horizontally polarizing black surface of the oil (Figure 3b) attracts large numbers of polarotactic aquatic insect species. These insects lure various insectivorous birds and bats, which are then trapped by the sticky oil (Figure 5c, d). The carcasses of these birds and bats in turn attract other carnivorous birds (eg owls, kestrels, hawks), which may also become trapped in the oil. Ancient natural asphalt seeps have acted as massive animal traps, the most famous example of which are the Rancho La Brea tar pits in Los Angeles, California (Akersten *et al.* 1983). It is generally thought that animals were initially caught when they accidentally stumbled into these tar pools, which may have been camouflaged by dust or leaves (Akersten *et al.* 1983). Alternatively, these asphalt seeps may sometimes have been covered by rainwater, thus strengthening their polarization signature and attracting polarotactic insects and birds, and initiating a cascading trap for predators attracted to the trapped prey species.

Population ecology

The attraction of aquatic insects to PLP sources is one of the most compelling and well-documented instances of ecological traps to date (Robertson and Hutto 2006). Ecological traps occur when rapid environmental change leads organisms to prefer to settle in poor-quality habitats (Gates and Gysel 1978); behavioral cues are no longer correlated with their expected fitness outcomes. Because PLP sources can polarize light more highly than water, aquatic insects prefer to settle and lay eggs upon artificial, horizontally polarizing surfaces, even when there are suitable water bodies nearby (Horváth *et al.* 1998, 2007; Kriska *et al.* 2008a). Ecological traps that result in mortality or reproductive failure are predicted to have severe fitness consequences, leading to rapid population declines and, in some cases, complete extirpation (Kokko and Sutherland 2001). Because the most common response to PLP is attraction, and since highly and horizontally polarized light is more attractive than less polarized light (Horváth and Varjú 2004), supernormal polarization signatures may be a common mechanism for triggering ecological traps among polarization-sensitive taxa.

Because population-scale studies of the effects of PLP are just beginning, its ability to cause population declines or alter the structure, diversity, or dynamics of ecological communities is still speculative. For example, populations of certain aquatic insect groups (eg mayflies and dragonflies) are declining in countries with highly dense human populations, but this could result solely from habitat alteration and destruction. Experimental approaches would address the importance of PLP by using large, temporary, polarization traps near aquatic habitats that are otherwise unaffected by PLP. Subsequent changes in the local population size of polarization-sensitive species, their biotic interactions with other organisms (eg competition, predation), and alterations in community structure or diversity could then be attributed to the effects of PLP. Observational studies could indirectly assess the effects of PLP by comparing populations of polarotactic taxa and their aquatic communities in wetland or riparian landscapes surrounded by varying acreages of artificial polarizers (eg asphalt roads and glass buildings).

Conclusions

The surprising ubiquity of anthropogenic polarizing surfaces combined with the occurrence of sensitivity to polarized light in so many animal taxa suggest that caution in the placement and use of artificial polarizers is warranted from a conservation perspective. Great potential exists for the mitigation and elimination of the ecological consequences of PLP, through the use of alternative materials that reduce the polarization signature of human activity. Because rough surfaces reflect light with lower p values at a given angle of reflection (Kriska *et al.* 2006b), one solution is to use building materials that are as rough as possible (eg avoiding shiny bricks and glass in favor of matte surfaces). Where shiny materials cannot be avoided, lighter-colored building materials should be used in place of shiny dark (black, dark gray, or dark-colored) ones. Night lighting in parking lots and near buildings should be minimized and/or directed away from buildings, asphalt, and cars. It is particularly important for these guidelines to be implemented in proximity to rivers, lakes, and other water bodies. Because polarotactic organisms can also use cues other than polarized light in selecting habitats, even relatively moderate reductions in the polarized light signature associated with human structures (eg with a degree of polarization more typical of natural habitats) may allow organisms to make adaptive decisions.

Although it is clear that the extent of PLP in natural environments is likely to increase proportionally to the enhanced use of artificial polarizers in human endeavors, the magnitude of the ecological consequences associated with increases in PLP is still difficult to predict with certainty. Future research needs regarding PLP can be grouped into two major categories: (1) monitoring and measuring the sources of PLP with imaging polarimetry, and (2) probing the organismal and ecological consequences of PLP. Surveying the human-made optical environment to establish further possible sources of PLP is essential. For example, photovoltaic solar panels are a possible source of PLP (Figure 6a), and production of these is predicted to increase in response to rising energy prices.

Research continues to add to the surprisingly long list of animals that have evolved the ability to detect polarization as well as to describe fascinating new uses for it. Yet our knowledge of the functional nature and the importance of polarization sensitivity in animals remains relatively limited. Because some organisms (eg polarotactic insects) are attracted not only by linearly polarized light, but also by artificial night lights, we need to investigate the synergistic interactions between polarotaxis

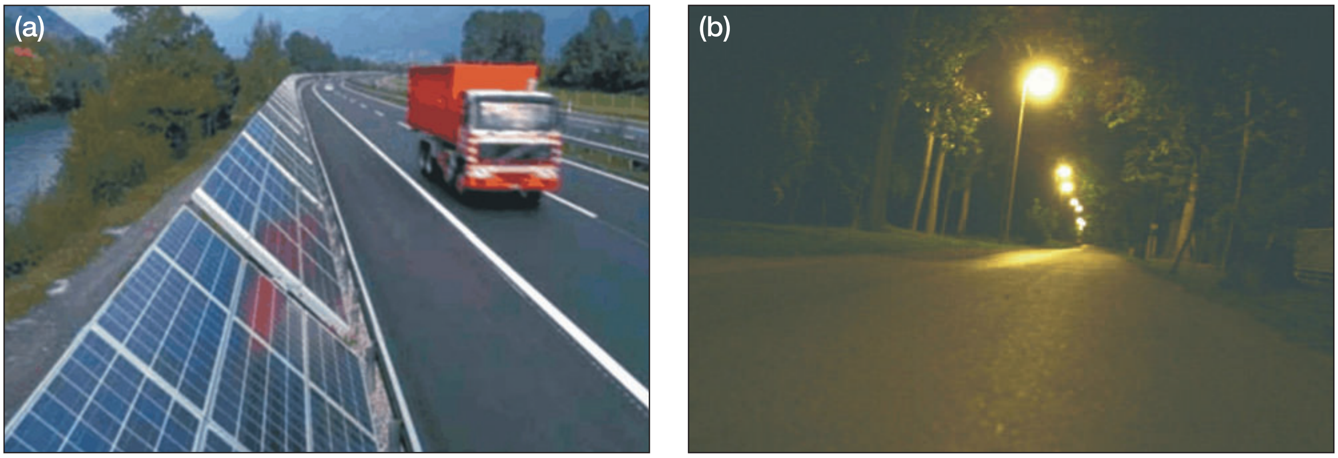

Figure 6. *PLP sources to be studied. (a) The PLP induced by the shiny, black surface of photovoltaic solar panels at the edge of an asphalt road running alongside a river bank is synergetically strengthened by the PLP caused by the asphalt surface. (b) The PLP of asphalt roads illuminated by streetlamps at night is synergetically supported by the photopollution of the lamps. Night-flying polarotactic insects may be lured by phototaxis to the streetlamps, and are then attracted to the horizontally polarizing asphalt.*

and phototaxis in the behavioral ecology of these species (Figure 6b). In addition to their diurnal effects, artificial lights illuminate a vast array of marine and freshwater habitats at night, in both urban and rural areas. Night lighting is a major source of ELP, but can also produce PLP via (1) reflection from buildings and other structures (Figures 2 and 3) and (2) the creation of underwater polarization signatures through scattering in the hydrosphere, which may affect ecological interactions among aquatic organisms.

Because the advantages of sensitivity to polarized light in some taxa are still unclear, forecasting the importance of PLP to the survival of populations and the integrity and function of ecosystems remains largely speculative. Even so, the ever-increasing levels of PLP and its ability to negatively affect behaviors and to alter interspecific interactions constitute an important conservation problem, which requires increased attention from conservation professionals and researchers alike.

■ Acknowledgments

GH is grateful for the equipment donation of the Alexander von Humboldt Foundation. This work was supported by the grant OTKA K-6846 of the Hungarian Science Foundation. We thank our colleagues S Andrikovics, B Bernáth, P Boda, Z Csabai, B Meyer-Rochow, G Molnár, R Schwind, G Szedenics, D Varjú, R Wehner, H Wildermuth, and J Zeil for their cooperation.

■ References

Akersten WA, Shaw CA, and Jefferson GT. 1983. Rancho La Brea: status and future. *Paleobiol* **9**: 211–17.

Bernáth B, Szedenics G, Molnár G, *et al.* 2001a. Visual ecological impact of a peculiar waste oil lake on the avifauna: dual-choice field experiments with water-seeking birds using huge shiny black and white plastic sheets. *Arch Nature Conserv Landsc Res* **40**: 1–28.

Bernáth B, Szedenics G, Molnár G, *et al.* 2001b. Visual ecological impact of "shiny black anthropogenic products" on aquatic insects: oil reservoirs and plastic sheets as polarized traps for insects associated with water. *Arch Nature Conserv Landsc Res* **40**: 89–109.

Bernáth B, Kriska G, Suhai B, and Horváth G. 2008. Wagtails (Aves: Motacillidae) as insect indicators on plastic sheets attracting polarotactic aquatic insects. *Acta Zool Acad Sci H* **54**: 145–55.

Bugoni L, Krause L, and Petry MV. 2001. Marine debris and human impacts on sea turtles in southern Brazil. *Marine Pollut Bull* **42**: 1330–34.

Coulson KL. 1988. Polarization and intensity of light in the atmosphere. Hampton, VA: A Deepak Publishing.

Dacke M, Nilsson ED, Scholtz CH, *et al.* 2003. Insect orientation to polarized moonlight. *Nature* **424**: 33.

Danthanarayana W and Dashper S. 1986. Response of some night-flying insects to polarized light. In: Danthanarayana W (Ed). Insect flight: dispersal and migration. Berlin, Germany: Springer-Verlag.

Derraik J. 2002. The pollution of the marine environment by plastic debris: a review. *Marine Poll Bull* **44**: 842–52.

Duguy R, Moriniere P, and Lemilinaire C. 1998. Factors of mortality of marine turtles in the Bay of Biscay. *Oceanol Acta* **21**: 383–88.

Eisenbeis G. 2006. Artificial night lighting and insects: attraction of insects to streetlamps in a rural setting in Germany. In: Rich C and Longcore T (Eds). Ecological consequences of artificial night lighting. Washington, DC: Island Press.

Gates JE and Gysel LW. 1978. Avian nest dispersion and fledging success in field–forest ecotones. *Ecology* **59**: 871–83.

Gramentz D. 1988. Involvement of loggerhead turtle with the plastic, metal and hydrocarbon pollution in the central Mediterranean. *Marine Pollut Bull* **19**: 11–13.

Henze MJ and Labhart T. 2007. Haze, clouds and limited sky visibility: polarotactic orientation of crickets under difficult stimulus conditions. *J Exp Biol* **210**: 3266–76.

Horváth G and Zeil J. 1996. Kuwait oil lakes as insect traps. *Nature* **379**: 303–04.

Horváth G, Bernáth B, and Molnár G. 1998. Dragonflies find crude oil visually more attractive than water: multiple-choice experiments on dragonfly polarotaxis. *Naturwissenschaften* **85**: 292–97.

Horváth G and Varjú D. 2004. Polarized light in animal vision–polarization patterns in nature. Berlin, Germany: Springer-Verlag.

Horváth G, Malik P, Kriska G, and Wildermuth H. 2007.

Ecological traps for dragonflies in a cemetery: the attraction of *Sympetrum* species (Odonata: Libellulidae) by horizontally polarizing black gravestones. *Freshwater Biol* **52**: 1700–09.

Horváth G and Kriska G. 2008. Polarization vision in aquatic insects and ecological traps for polarotactic insects. In: Lancaster J and Briers RA (Eds). Aquatic insects: challenges to populations. Wallingford, UK: CAB International Publishing.

Horváth G and Pomozi I. 1997. How celestial polarization changes due to reflection from the deflector panels used in deflector loft and mirror experiments studying avian navigation. *J Theor Biol* **184**: 291–300.

Horváth G, Majer J, Horváth L, *et al*. 2008. Ventral polarization vision in tabanids: horseflies and deerflies (Diptera: Tabanidae) are attracted to horizontally polarized light. *Naturwissenschaften* **95**: 1093–1100.

Kokko H and Sutherland WJ. 2001. Ecological traps in changing environments: ecological and evolutionary consequences of a behaviourally mediated Allee effect. *Evol Ecol Res* **3**: 537–51.

Kovarov BG and Monchadskiy AS. 1963. About the application of polarized light in light-traps to catch insects. *Entomologicheskow Obozrenie* **42**: 49–55.

Können GP. 1985. Polarized light in nature. Cambridge, UK: Cambridge University Press.

Kriska G, Horváth G, and Andrikovics S. 1998. Why do mayflies lay their eggs en masse on dry asphalt roads? Water-imitating polarized light reflected from asphalt attracts Ephemeroptera. *J Exp Biol* **201**: 2273–86.

Kriska G, Csabai Z, Boda P, *et al*. 2006a. Why do red and dark-coloured cars lure aquatic insects? The attraction of water insects to car paintwork explained by reflection–polarisation signals. *P Roy Soc B* **273**: 1667–71.

Kriska G, Malik P, Csabai Z, and Horváth G. 2006b. Why do highly polarizing black burnt-up stubble-fields not attract aquatic insects? An exception proving the rule. *Vision Res* **46**: 4382–86.

Kriska G, Bernáth B, and Horváth G. 2007. Positive polarotaxis in a mayfly that never leaves the water surface: polarotactic water detection in *Palingenia longicauda* (Ephemeroptera). *Naturwissenschaften* **94**: 148–54.

Kriska G, Malik P, Szivák I, and Horváth G. 2008a. Glass buildings on river banks as "polarized light traps" for mass-swarming polarotactic caddis flies. *Naturwissenschaften* **95**: 461–67.

Kriska G, Barta A, Suhai B, *et al*. 2008b. Do brown pelicans mistake asphalt roads for water in deserts? *Acta Zool Acad Sci H* **54**: 157–65.

Labhart T and Meyer EP. 2002. Neural mechanisms in insect navigation: polarization compass and odometer. *Curr Opin Neurobiol* **12**: 707–14.

Longcore T and Rich C. 2004. Ecological light pollution. *Front Ecol Environ* **2**: 191–98.

Lythgoe JN and Hemmings CC. 1967. Polarized light and underwater vision. *Nature* **213**: 893–94.

Malik P, Hegedüs R, Kriska G, and Horváth G. 2008. Imaging polarimetry of glass buildings: why do vertical glass surfaces attract polarotactic insects? *Appl Optics* **47**: 4361–74.

Marshall J, Cronin TW, Shashar N, and Land M. 1999. Behavioural evidence for polarisation vision in stomatopods reveals a potential channel for communication. *Curr Biol* **9**: 755–58.

McCauley SJ and Bjorndal KA. 1999. Conservation implications of dietary dilution from debris ingestion: sublethal effects in post-hatchling loggerhead sea turtles. *Conserv Biol* **13**: 925–29.

McIntyre JW and Barr JF. 1997. Common loon (*Gavia immer*). In: Poole A (Ed). The birds of North America online. Ithaca, NY: Cornell Lab of Ornithology.

Montevecchi WA and Stenhouse IJ. 2002. Dovekie (*Alle alle*). In: Poole A (Ed). The birds of North America online. Ithaca, NY: Cornell Lab of Ornithology.

Novales Flamarique I and Browman HI. 2001. Foraging and prey-search behaviour of small juvenile rainbow trout (*Oncorhynchus mykiss*) under polarized light. *J Exp Biol* **204**: 2415–22.

Nowinszky L. 2003. The handbook of light trapping. Szombathely, Hungary: Savaria University Press.

Parker H. 1984. Effect of corvid removal on reproduction of willow ptarmigan and black grouse. *J Wildl Manage* **48**: 1197–1205.

Rich C and Longcore T. 2006. Ecological consequences of artificial night lighting. Washington, DC: Island Press.

Robertson BA and Hutto RL. 2006. A framework for understanding ecological traps and an evaluation of existing evidence. *Ecology* **87**: 1075–85.

Schwind R. 1985. Sehen unter und über Wasser, sehen von Wasser. *Naturwissenschaften* **72**: 343–52.

Schwind R. 1991. Polarization vision in water insects and insects living on a moist substrate. *J Comp Physiol A* **169**: 531–40.

Schwind R. 1995. Spectral regions in which aquatic insects see reflected polarized light. *J Comp Physiol* **177**: 439–48.

Shashar N, Hanlon RT, and Petz AM. 1998. Polarization vision helps detect transparent prey. *Nature* **393**: 222–23.

Tovée MJ. 1995. Ultra-violet photoreceptors in the animal kingdom: their distribution and function. *Trends Ecol Evol* **10**: 455–60.

Umow N. 1905. Chromatische depolarisation durch Lichtzerstreuung. *Phys Z* **6**: 674–76.

von Frisch K. 1967. The dance language and orientation of bees. Cambridge, MA: Belknap Press/Harvard University Press.

Waterman TH. 2006. Reviving a neglected celestial underwater polarization compass for aquatic animals. *Biol Rev* **81**: 111–15.

Wehner R. 2001. Polarization vision – a uniform sensory capacity? *J Exp Biol* **204**: 2589–96.

Wehner R and Labhart T. 2006. Polarization vision. In: Warrant EJ and Nilsson DE (Eds). Invertebrate vision. Cambridge, UK: Cambridge University Press.

Wildermuth H. 1998. Dragonflies recognize the water of rendezvous and oviposition sites by horizontally polarized light: a behavioural field test. *Naturwissenschaften* **85**: 297–302.

Wildermuth H and Horváth G. 2005. Visual deception of a male *Libellula depressa* by the shiny surface of a parked car (Odonata: Libellulidae). *Int J Odonatol* **8**: 97–105.

Conservation Biology

Contributed Paper

Reducing the Maladaptive Attractiveness of Solar Panels to Polarotactic Insects

GÁBOR HORVÁTH,* MIKLÓS BLAHÓ,* ÁDÁM EGRI,* GYÖRGY KRISKA,† ISTVÁN SERES,‡ AND BRUCE ROBERTSON§

*Environmental Optics Laboratory, Department of Biological Physics, Physical Institute, Eötvös University, H-1117 Budapest, Pázmány sétány 1, Hungary
†Group for Methodology in Biology Teaching, Biological Institute, Eötvös University, H-1117 Budapest, Pázmány sétány 1, Hungary
‡Szent István University, Department of Physics and Process Control, H-2103 Gödöllő, Páter utca 1, Hungary
§DOE Great Lakes Bioenergy Research Center, Michigan State University, East Lansing, MI 48824, U.S.A., email roberba1@msu.edu

Abstract: *Human-made objects (e.g., buildings with glass surfaces) can reflect horizontally polarized light so strongly that they appear to aquatic insects to be bodies of water. Insects that lay eggs in water are especially attracted to such structures because these insects use horizontal polarization of light off bodies of water to find egg-laying sites. Thus, these sources of polarized light can become ecological traps associated with reproductive failure and mortality in organisms that are attracted to them and by extension with rapid population declines or collapse. Solar panels are a new source of polarized light pollution. Using imaging polarimetry, we measured the reflection–polarization characteristics of different solar panels and in multiple-choice experiments in the field we tested their attractiveness to mayflies, caddis flies, dolichopodids, and tabanids. At the Brewster angle, solar panels polarized reflected light almost completely (degree of polarization* $d \approx 100\%$*) and substantially exceeded typical polarization values for water (*$d \approx 30$*–*70%*). Mayflies (Ephemeroptera), stoneflies (Trichoptera), dolichopodid dipterans, and tabanid flies (Tabanidae) were the most attracted to solar panels and exhibited oviposition behavior above solar panels more often than above surfaces with lower degrees of polarization (including water), but in general they avoided solar cells with nonpolarizing white borders and white grates. The highly and horizontally polarizing surfaces that had nonpolarizing, white cell borders were 10- to 26-fold less attractive to insects than the same panels without white partitions. Although solar panels can act as ecological traps, fragmenting their solar-active area does lessen their attractiveness to polarotactic insects. The design of solar panels and collectors and their placement relative to aquatic habitats will likely affect populations of aquatic insects that use polarized light as a behavioral cue.*

Keywords: evolutionary trap, habitat selection, maladaptation, polarized light pollution

Reducción de la Atracción Inadaptiva de Placas Solares para Insectos Polarotácticos

Resumen: *Objetos construidos por humanos (e. g., edificios con superficies de vidrio) pueden reflejar luz polarizada horizontalmente tan potentemente los insectos acuáticos los confunden por cuerpos de agua. Los insectos que ovopositan en el agua son especialmente atraídos por tales estructuras porque estos insectos utilizan la polarización horizontal de luz de los cuerpos de agua para encontrar sitios para la puesta de huevos. Por lo tanto, estas fuentes de luz polarizada pueden convertirse en trampas ecológicas asociadas con el fracaso reproductivo y mortalidad de organismos que son atraídos a ellas y por extensión, con declinaciones poblacionales rápidas o colapso. Las placas solares son una fuente de contaminación por luz polarizada. Utilizando polarimetría de imágenes, medimos las características de reflexión-polarización de diferentes placas solares y, en experimentos de opción múltiple en el campo, probamos su atracción en efemerópteros, tricópteros, dolicopódidos y tabánidos. Las placas solares polarizaron la luz reflejada casi totalmente (nivel*

Paper submitted October 13, 2009; revised manuscript accepted January 19, 2010.

DOI: 10.1111/j.1523-1739.2010.01518.x

de polarización d *≈ 100%) y excedieron sustancialmente los valores típicos de polarización del agua (*d *≈ 30–70%). Los efemerópteros, tricópteros, dípteros dolicopódidos y tábanos fueron los más atraídos a las placas solares y exhibieron comportamiento de ovoposición sobre las placas solares más a menudo que sobre superficies con niveles de polarización más bajos (incluyendo agua), pero en general evitaron las celdas solares con bordes blancos no polarizadores y rejillas blancas. Las superficies alta y horizontalmente polarizadoras que tenían celdas blancas no polarizadoras fueron entre 10 y 26 veces menos atractivas para insectos que las mismas placas sin divisiones blancas. Aunque las placas solares pueden actuar como trampas ecológicas, la fragmentación de su área solar activa no disminuye su atracción de insectos polarotácticos. El diseño de placas y colectores solares y su colocación en relación con hábitats acuáticos muy probablemente afectará poblaciones de insectos acuáticos que utilizan luz polarizada como una señal conductual.*

Palabras Clave: contaminación por luz polarizada, inadaptación, selección de hábitat, trampa evolutiva

Introduction

Rapidly changing environments have the potential to disrupt evolved behaviors because the environmental cues organisms use to direct their behavior may no longer elicit the outcome with which they were associated historically (Levins 1968). Evolutionary traps occur when rapid environmental change triggers organisms to make maladaptive behavioral decisions (Schlaepfer et al. 2002). Although evolutionary traps may be associated with any behavior (e.g., mate selection, navigation, nest-site selection), the most empirically and theoretically well-understood type of evolutionary trap is the ecological trap. Ecological traps are situations in which novel environmental conditions lead organisms to settle in poor-quality habitats (Dwernychuk & Boag 1972). They represent severe cases of behavioral maladaptation that can lead to population declines or extirpation (Delibes et al. 2001; Kokko & Sutherland 2001). Despite the awareness of ecological traps among ecologists and conservation biologists, fewer than 10 cases have been well documented (reviewed by Robertson & Hutto 2006, 2007; Hedin et al. 2008; Carrete et al. 2009; Resetarits & Binckley 2009).

Shiny dark-colored objects such as oil lakes and glass buildings can reflect highly and horizontally polarized light. Positively polarotactic aquatic insects that use horizontally polarized light to detect water are attracted to these objects (Schwind 1991; Horváth & Zeil 1996; Horváth et al. 1998; Wildermuth 1998; Kriska et al. 2008). Sunlight is unpolarized, because it consists of electromagnetic waves of different wavelengths and vibrating at all possible planes perpendicular to the direction of propagation, but light is completely linearly polarized when its waves oscillate only in a single plane. The smooth surface of water horizontally polarizes reflected sunlight and skylight, and this reflection is an evolutionarily reliable cue that indicates the presence of lakes and rivers to over 300 species of aquatic insects (e.g., Schwind 1995; Wildermuth 1998; Horváth & Kriska 2008). Polarized light pollution (Horváth et al. 2009) produced by human-made objects can be so severe that it creates ecological traps in which insects tend to mate above and oviposit on artificial surfaces, where they are subject to increased predation and reproductive failure (Kriska et al. 1998; Horváth & Varjú 2004).

In general, dark and smooth materials reflect light with a high degree of polarization and so are highly likely to attract polarotactic organisms. The use of photovoltaic solar cells and solar collectors as a source of energy is likely to increase dramatically yet the physical characteristics of the cells and collectors suggest they may represent a major new source of polarized light pollution (Figs. 1 & 2; Supporting Information). We examined the attractiveness of photovoltaic solar panels and artificial surfaces of varying brightness and smoothness to some polarotactic aquatic insects (*Philopotamus*: Trichoptera; dolichopodids: Diptera; mayflies: Ephemeroptera; tabanid flies: Tabanidae) and used imaging polarimetry (Horváth & Varjú 1997) to quantify the reflection–polarization characteristics of these surfaces.

Methods

Choice Experiments with Mayflies, Caddis Flies, and Dolichopodids

We conducted five experiments in the Hungarian Duna-Ipoly National Park at Dömörkapu, in which we monitored the response of Ephemeroptera, Trichoptera, and dolichopodid dipteran species to (1) white-framed solar cells and nonpolarizing surfaces, (2) white- and black-framed solar cells with an underlying polarizing plastic sheeting, (3) white- and black-framed solar cells in the absence of an underlying polarizing plastic sheeting, (4) shiny black surfaces with different nonpolarizing white grid patterns, and (5) white framing of solar cells in a solar panel versus a homogeneously black solar panel.

The insects we examined in the park emerged from a creek adjacent to the site of the experiments at dusk from May to July and swarmed above the water surface and portions of a dry asphalt road that reflected highly and horizontally polarized light near sunset. Insects mate in swarms that develop from 17:00 to 21:00 h, and fertilized females oviposit directly onto water or other horizontally polarizing surfaces immediately afterward (Horváth & Kriska 2008). In earlier field experiments performed

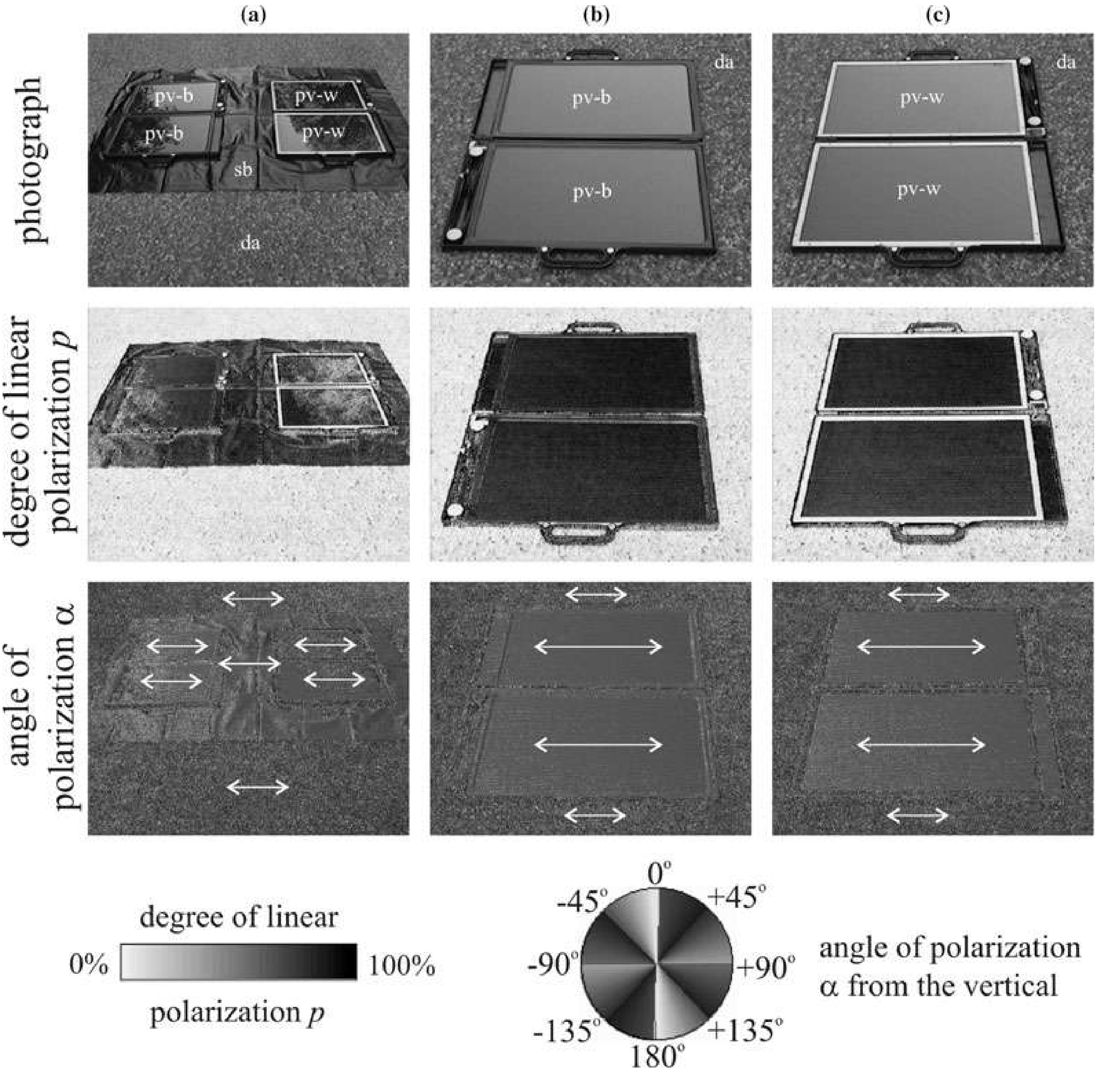

Figure 1. Photographs and reflection-polarization patterns of the shiny black (sb) plastic sheet (2 × 2 m; other surfaces 80 × 60 cm), white-framed photovoltaic solar cells (pv-w), black-framed photovoltaic solar cells (pv-b), shiny black plastic sheet (sb), and dry asphalt (da) measured in the green (550 nm) part of the spectrum after sunset. Double-headed arrows show the direction of polarization of reflected light. The polarimeter viewed toward the antisolar meridian and the angle of elevation of its optical axis was −35° from the horizontal.

at the same site (Kriska et al. 1998; Horváth & Varjú 2004; Horváth & Kriska 2008), these taxa more often reproduced over artificial surfaces that reflected highly and horizontally polarized light than over water, and displayed the same reproductive behavior above human-made, shiny, dark surfaces and water surfaces.

On 21 May 2008 we tested the relative attractiveness of white-framed solar cells and nonpolarizing test surfaces of different reflectivity to polarotactic taxa. We laid a sheet of shiny black plastic (2 × 2 m) flat on a dry asphalt road on which we placed a matte black cloth (80 × 60 cm), a matte white cloth, and a photovoltaic solar panel (13 W, Solar Generator, Conrad Electronic, Budapest, Hungary) of the same size equidistant from each other and the edges of the sheet (Supporting Information). The photovoltaic panel was composed of two white-framed (frame width 1 cm) photovoltaic solar cells (each 60 × 40 cm). The fourth test surface was an area of the black plastic sheeting equivalent in size to the other surfaces. We repositioned the test surfaces on the plastic

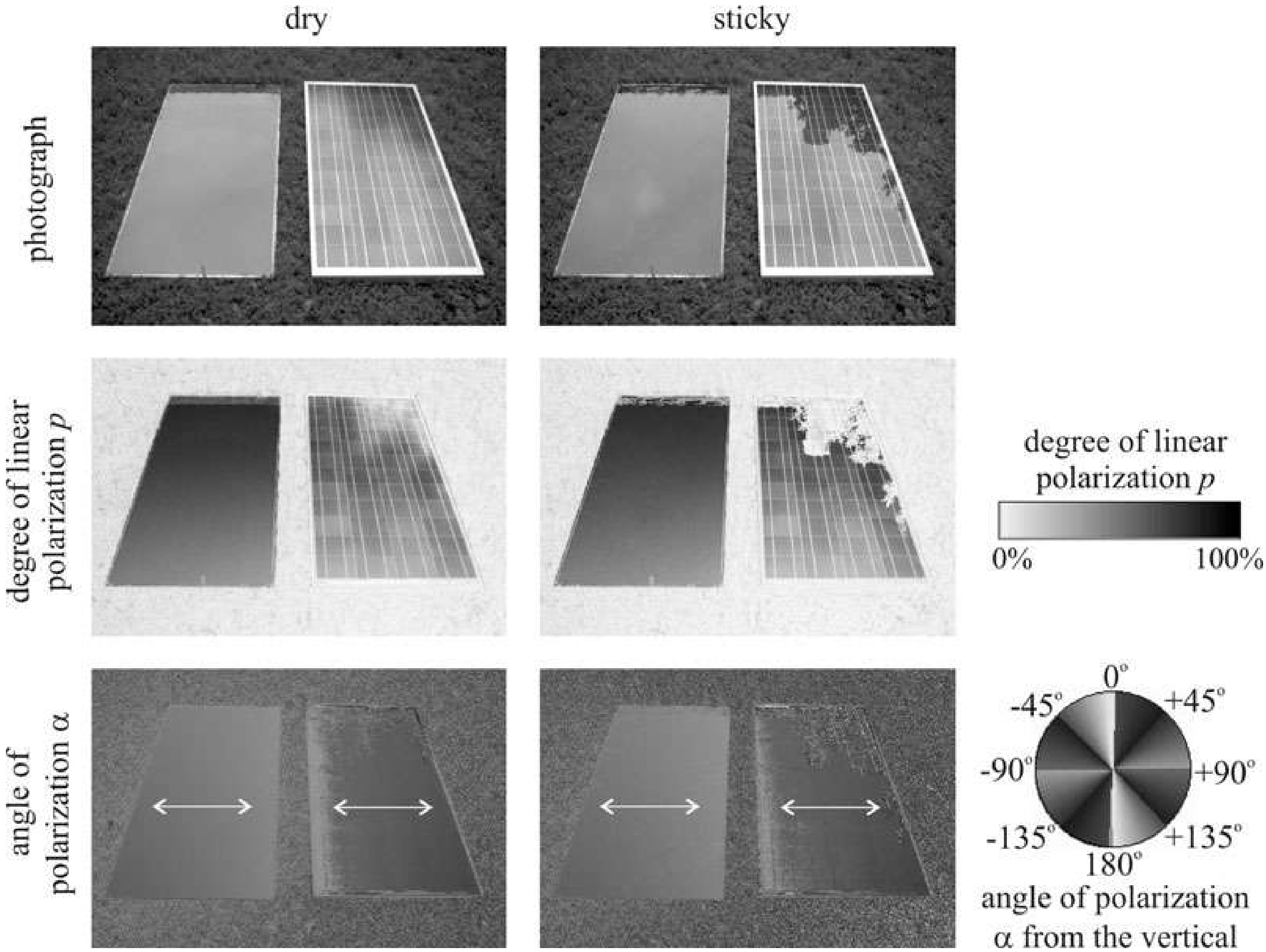

Figure 2. Photographs and reflection-polarization patterns of the two horizontal (dry and sticky) solar panels used in the choice experiments with mayflies, caddis flies, dolichopodids, and tabanids. Double-headed arrows show the direction of polarization of reflected light. The polarimeter viewed toward the antisolar meridian and the angle of elevation of its optical axis was −35° from the horizontal.

sheet randomly every 30 min over the course of each experiment. Mayflies hover over and land repeatedly on surfaces prior to oviposition (Savolainen 1978; Supporting Information), so we inferred attractiveness from the number of mayflies (N_M) and the number of landings (N_L) made by individuals on each test surface.

On 22 May 2008 we tested whether the original white, nonpolarizing (degree of linear polarization of reflected light $d \approx 0\%$) frame (width 1 cm) around the two solar cells reduced their attractiveness to mayflies. The manufacturer (Conrad Electronic) described this white frame as purely decorative. We used two solar panels of identical size (80 × 60 cm) (Fig. 1a). The first had the original white frame. On the second, the white frame was covered with a highly ($d \approx 100\%$) and horizontally polarizing, shiny, black plastic tape (width 1 cm). We counted the number of mayflies and the number of landings made by individuals on both solar panels. These two panels were transposed on the black plastic sheet every 15 min throughout the 2-h experiment.

For 5 days between 23 and 30 May 2008, we tested mayfly attraction to a white-framed and a black-framed solar panel in the absence of the underlying polarizing plastic sheeting. The protocols were identical to the preceding experiment, but the underlying substrate of the two differently framed solar panels was a weakly polarizing ($d < 15\%$) section of the dry asphalt road (Figs. 1b-c).

For 8 days between 23 May to 3 June 2008, we tested the effect of nonpolarizing white grid patterns on the attractiveness of shiny black surfaces to mayflies. Given the typically deleterious effects of habitat fragmentation on the abundance and species richness of species in natural systems (e.g., Collinge 2000; Funk et al. 2005; Moore et al. 2008), we tested whether partitioning even highly and horizontally polarizing surfaces into smaller sections could make them unattractive to polarotactic insects. Because the operative nature of attraction of all known taxa of polarotactic aquatic insects to water is its polarized light signature (dragonflies: Wildermuth 1998;

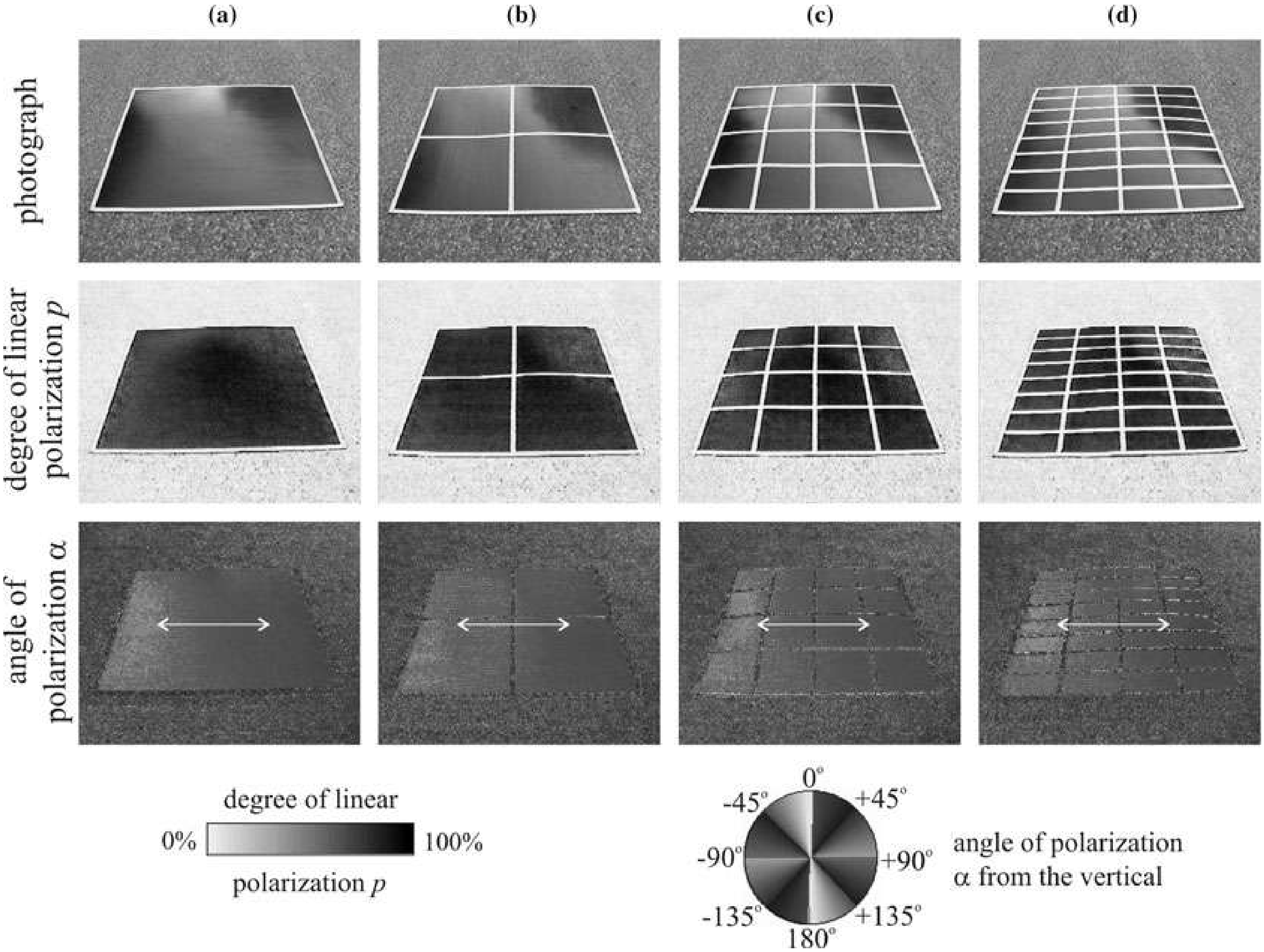

Figure 3. Photographs and reflection-polarization patterns of the four polarizing surfaces (2 × 2 m) used in the experiment with mayflies, caddis flies, and dolichopodids (Fig. 4). The white-framed surfaces (b, c, d) are orthogonally partitioned by nonpolarizing white tape. Double-headed arrows show the direction of polarization of reflected light. The polarimeter viewed toward the antisolar meridian and the angle of elevation of its optical axis was −35° from the horizontal.

78 aquatic beetles [Coleoptera] and 21 aquatic bugs [Heteroptera]: Csabai et al. 2006; 37 aquatic Coleopteran and Heteropteran taxa: Kriska et al. 2006), we created test surfaces of highly polarizing smooth black plastic (Bernáth et al. 2001). We made four shiny black plastic squares (2 × 2 m) with a white frame (width 1 cm) on their outer edge. Three of the white-framed squares were orthogonally partitioned by white tape (width 1 cm) with a low d (< 5%) that effectively fragmented the total area of black polarizing surface into smaller fragments (A, 1 section; B, 4 sections; C, 16; D, 32; Fig. 3). We covered surfaces with a colorless and odorless transparent paraffin oil, which made them sticky so that insects landing on them would be instantly trapped. Every 30 min we randomly repositioned test panels within their linear formation on an underlying substrate of weakly polarizing (d < 15%) dry asphalt road. Test surfaces were placed on the asphalt road 50 cm apart, parallel to the river, and exposed from 19:00 and 21:00 h. Trapped insects were collected at the end of each 2-h session, stored in alcohol, and later identified in the laboratory. We calculated the density of Emphemeroptera, Trichoptera, and dolichopodid Dipterans captured per unit black area on test surfaces. Ephemeropterans were identified to the species level.

We repeated the procedure we used with the shiny black surfaces fragmented by different white grid patterns with (1) a white-framed (width 1 cm) solar panel (100 W, RWE Schott Solar, Alzenau, Germany) composed of solar cells that were small, homogeneous, shiny black, and rectangular with narrow (width 0.2–0.5 cm) white margins (Fig. 2; Supporting Information) and (2) a homogenous black solar panel (40 W, DunaSolar, Budapest, Hungary) with no white partitioning (Fig. 2; Supporting

Table 1. The surface density[a] of polarotactic dolichopodids (Diptera) trapped by the homogeneous black and white-gridded solar panels

Date 2009	*Black[b]*	*White gridded*
3 June	111.9	15.8
8 June	185.7	47.3
9 June	136.9	55.8
10 June	75.0	32.7
12 June	135.7	78.8
14 June	161.9	32.7
15 June	77.4	43.6
16 June	109.5	46.1
17 June	98.8	40.0
18 June	92.9	49.7
Sum	1185.7	442.4

[a] *Surface density:* $n = m \times 1\ m^2/A$, *where* m *is the number of insects counted on the surface,* A *is the amount of black area;* n, *is the number of dolichopodids trapped by 1* m^2 *of sticky black surface. For the homogeneous black solar panel and the white-gridded solar panel* A *was 0.84 and 0.825* m^2*, respectively.*
[b] *On all dates for the black surface, the difference in the sum of* n ($\chi^2 = 338.4$, $df = 1$, $p < 0.0001$) *and the daily differences in* n ($\chi^2 = 8.9 - 84.5$, $df = 1$, $p < 0.005$) *were highly statistically significant.*

Information) to examine whether behavioral responses to test surfaces were representative of responses to manufactured solar panels. Narrow white cell divisions created 144 black squares that were slightly heterogeneous in size (Fig. 2; Supporting Information). We laid the panels on the dry asphalt road 1-m apart and exchanged their position every 30 min. Although the area of both surfaces was identical (1.2 × 0.7 m), the net black area of the panel with the white grid was slightly smaller (0.825 m^2) than the black area of the panel that was entirely black (0.84 m^2), so we calculated the number of insects captured per unit black area (Tables 1 & 2). For 10 days between 3 and 18 June 2009 between 18:00 and 21:00 h, we counted dolichopodids and mayflies because these taxa were the most abundant at the study site.

Choice Experiment with Tabanids

On 2 sunny, warm days (9 and 11 July 2009, between 10:00 and 18:00 h each day), we conducted experiments at a horse farm in Szokolya (47°52′N, 19°00′E), Hungary. We used the same two solar panels as in the experiment with sticky panels that trapped mayflies and dolichopodids, but the panels did not have sticky paraffin oil on them (Fig. 2). We laid both test surfaces horizontally on grassy ground 1-m apart and switched their positions every 30 min. We made sure both panels were in either sun or shade at the same time. Thus, their temperatures (measured by a digital contact thermometer with an accuracy of 0.25 °C) were the same. We counted the number of tabanid flies touching the dry solar panels and expressed the number of "captures" relative to the amount of black surface on the panels (Table 3). We did not use the paraffin oil to capture flies because we learned in a preliminary test that it did not capture tabanids. We acknowledge our method in this experiment is affected by pseudoreplication (i.e., the same tabanid individual may have been counted more than once). In spite of this, we believe the conclusions we drew from the number of tabanids touching the dry solar panels are valid because the attractiveness of the surfaces to tabanids is proportional to the number touching the surfaces.

We performed binomial χ^2 tests in Statistica (version 6.0) to compare numbers of captures, abundance, and touches among test surfaces for each insect taxon investigated.

Imaging Polarimetry

We measured reflection–polarization characteristics of solar panels and test surfaces by imaging polarimetry in the red (650 ± 40 nm = wavelength of maximal sensitivity ± half bandwidth of the detectors of the polarimeter), green (550 ± 40 nm), and blue (450 ± 40 nm) parts of the spectrum. Our method of imaging polarimetry is described in detail elsewhere (Horváth & Varjú 1997, 2004). We provide only the polarization patterns measured in the green spectral range. Similar patterns were obtained in the red and blue parts of the spectrum because the targets were colorless (black, gray, or white); thus, their reflection–polarization characteristics did not depend on the wavelength of light. Polarimetry was performed under clear skies after sunset or in full sun.

Table 2. The surface density *n* of polarotactic mayflies (Ephemeroptera) trapped by the homogeneous black and white-gridded solar panels.

Mayfly species	*Black**	*White gridded*
Baetis rhodani	271.4	50.9
Ephemera danica	142.9	2.4
Rhithrogena semicolorata	60.7	18.2
Sum	475.0	71.5

**For the black surface the difference in the sum of* n ($\chi^2 = 296.4$, $df = 1$, $p < 0.0001$) *and the differences in* n *for all three species* ($\chi^2 = 21.8$–149.5, $df = 1$, $p < 0.0001$) *were highly statistically significant.*

Results

At the Brewster angle ($\theta_{Brewster} = 56.3°$ from the vertical), solar cells ($d \approx 90$–100%) and black plastic sheeting ($d \approx 100\%$) were strong horizontal polarizers of incident light compared with the matte black ($d < 20\%$) and white ($d \approx 0\%$) test surfaces (Figs. 1 & 2; Supporting Information). Mayflies were attracted to the black plastic sheeting ($N_M = 126$, $N_L = 281$) and avoided ($N_M = N_L = 0$) the matte white and matte black surfaces and the white-framed solar cells ($p < 0.0001$, df = 1, N_M: $\chi^2 = 126$, N_L:

Table 3. The surface densities n_{touch} and n_{time} of the numbers of polarotactic tabanids (N_T) and their landings (N_L) on the homogeneous black and the white-gridded dry solar panels and the temporal preference[a] of these tabanids.

	$n_{tabanid}$		$n_{touch-down}$		t *(sec)*	
Date (2009)	*black*[b]	*white gridded*	*black*[b]	*white gridded*	*black*[b]	*white gridded*
9 July	95.2	32.7	625	84.8	6,078.6	987.9
11 July	145.2	38.8	781	77.6	5,006	535.8
Sum	240.5	71.5	1406	162.4	11,084.5	1523.6

[a] *Temporal preference:* $t = T \times 1\ m^2/A$, *where* T *is the time period spent by tabanids on a given test surface, the net black area of which is* A ($A_{black} = 0.84\ m^2$, $A_{whitegridded} = 0.825\ m^2$).

[b] *The differences in the sum of* $n_{tabanid}$, $n_{touchdown}$, *and* t *are statistically significant* ($n_{tabanid}$: $\chi^2 = 90.5$, $df = 1$, $p < 0.0001$; $n_{touchdown}$: $\chi^2 = 984.5$, $df = 1$, $p < 0.0001$; t : $\chi^2 = 7248.6$, $df = 1$, $p < 0.0001$). *The daily differences in* $n_{tabanid}$, $n_{touchdown}$, *and* t *are also statistically significant* ($n_{tabanid}$: $\chi^2 = 29.6$-60.4, $df = 1$, $p < 0.0001$; $n_{touchdown}$: $\chi^2 = 435.1$-574.6, $df = 1$, $p < 0.0001$; t : $\chi^2 = 3604.2$-3683.6, $df = 1$, $p < 0.0001$).

$\chi^2 = 281$). Mayflies avoided the white-framed solar cells ($N_M = N_L = 0$), but were attracted to the solar cells with polarizing black frames ($N_M = 43$, $N_L = 105$, $p < 0.0001$, df = 1, N_M: $\chi^2 = 43$, N_L: $\chi^2 = 105$; Fig. 1b). When we replaced the black plastic sheet with weakly polarizing dry asphalt ($d < 15\%$; Figs. 1b-c), the black-framed solar cells attracted 4.2 times more mayflies ($N_{M,\text{blackframed}} = 200$, $N_{M,\text{whiteframed}} = 48$, $\chi^2 = 93.1$, df = 1, $p < 0.0001$) and elicited 6.9 times more landings ($N_{M,\text{blackframed}} = 474$, $N_{M,\text{whiteframed}} = 69$, $\chi^2 = 302$, df = 1, $p < 0.0001$) than the white-framed solar cells (Supporting Information).

The relation between the number of orthogonal white stripes on a sticky test surface and the captures per unit black area for all taxa was negative (Fig. 4; Supporting Information). Captures per square meter were 26.5 and 10.3 times higher on the unpartitioned surface relative to the most highly partitioned surface for Trichopterans and dolichopodids, respectively. Mayfly captures per square meter were 16.7 times higher on the unpartitioned surface relative to the most highly partitioned surface, and responses were similar among the four mayfly species we captured (Supporting Information).

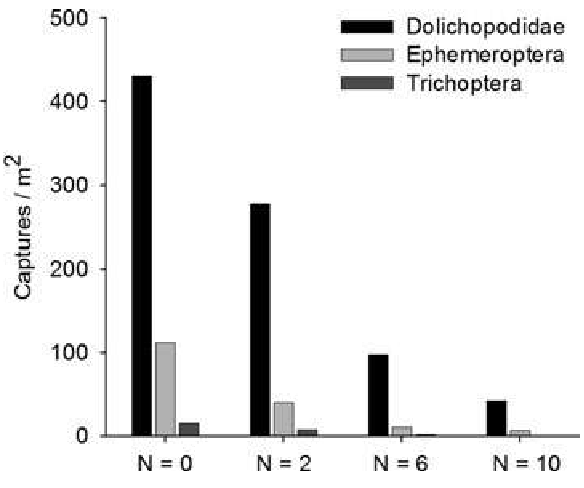

Figure 4. The surface density (captures per square meter) of polarotactic dolichopodid (Diptera), mayflies (Ephemeroptera), and Philopotamus *(Trichoptera) trapped by a highly and horizontally polarizing sticky surface with different numbers* (N) *of orthogonal white strips (Fig. 3).*

Captures (1186/m^2) of dolichopodids on the homogeneous black solar panel were 2.7 times higher than captures (442/m^2) on the partitioned white-gridded panel, which is a highly statistically significant difference (Table 1). The homogeneous panel (475/m^2) attracted mayflies 6.6 times more than the partitioned panel (72/m^2) (Table 2). We obtained similar results for the experiment with tabanid flies (Table 3). The homogeneous black solar panel (240.5/m^2) attracted tabanids 3.4 times more than the white-gridded panel (71.5/m^2). Tabanids touched down (1406/m^2) on the homogeneous panel 8.7 times more frequently than on the white-gridded panel (162.4/m^2). After landing, tabanids stayed (11084.5/m^2) on the homogeneous panel 7.3 times longer period than on the white-gridded panel (1523.6/m^2).

Figure 2 shows the reflection–polarization patterns of the two sticky and dry solar panels we used in the experiment with mayflies, caddis flies, dolichopodids, and tabanids, respectively. The dry and sticky solar panels had nearly the same reflection–polarization characteristics. Both the white frame and the white grid of the partitioned solar panel reflected weakly polarized or unpolarized light, whereas the other shiny black surface regions reflected highly polarized light as did the entire surface of the homogeneously black solar panel. The direction of polarization of light reflected from both panels was always horizontal when the plane of reflection was vertical.

Discussion

Our results demonstrate that photovoltaic solar panels produce polarized light pollution (Horváth et al. 2009). White-framed and white-gridded solar panels, however, were much less attractive to polarotactic aquatic insects than homogeneous black panels. Thus, the former panels induce much less polarized light pollution. The degree of polarization of light reflected from water bodies is typically <70%. Because of the near total ($d \approx 100\%$ at the Brewster angle) and horizontal polarization of light reflected from solar panels, polarotactic aquatic insects are likely to prefer artificial surfaces over natural bodies of water and to oviposit on the artificial surfaces. This polarization-induced attraction represents a severe form of ecological trap (Robertson & Hutto 2006) for polarotactic insects that will result in reproductive failure of eggs laid on artificial surfaces (e.g., Watson 1992; Vondel 1998; Kriska et al. 2006; Horváth et al. 2007), death from exhaustion, and increased risk of predation (Kriska et al. 1998; Horváth & Varjú 2004; Horváth & Kriska 2008). The solar panels we used were oriented horizontally to mimic the orientation of natural water bodies. Solar panels are often elevated above the ground and tilted at an angle to maximize interception of solar radiation. Orientation and elevation appear to be generally unimportant in mitigating behavioral responses of polarotactic insects to artificial polarizing reflectors. Vertical glass surfaces are highly effective at horizontally polarizing light (Malik et al. 2008) and attracting polarotactic aquatic insects to oviposit en masse even many stories above ground level (Kriska et al. 2008). It is well documented that aquatic beetles, water bugs and dragonflies are attracted to and oviposit on the roof, hood, and trunks of dark-colored highly polarizing automobiles that are elevated and tilted at various heights and angles (e.g., Jäch 1997; Nilsson 1997; Wildermuth & Horváth 2005). Consequently, we expect that tilted and even highly elevated solar panels will attract these insects. Elevation may even increase the distances at which such structures can be detected.

Our results show that a dense nonpolarizing (e.g., white) grid partitioning the solar-active area of solar panels reduces or eliminates the polarized light pollution of these highly and horizontally polarizing artificial surfaces. There is a trade-off, however, between the amount of solar-active surface and nonpolarizing grid: such grids will reduce the performance of these panels. The decrease in energy production associated with the application of a grid is proportional to the total surface area of the grid. The white-gridded solar panel (RWE Schott Solar) we used had a total surface area of 0.840 m^2, and the surface area of the white grid was 0.015 m^2. Thus, the solar-active (black) area was 0.825 m^2. This means there would be a 1.8% loss of effective (i.e., energy producing black) surface area in this panel, but a statistically significant reduction of the attractiveness of the panel to polarotactic insects. Thus, the cost of effectively eliminating the attractive effect of polarized light pollution on the taxa we investigated amounts to a relatively small drop in performance of solar panels.

The cognitive or behavioral mechanism reducing the attractiveness of partitioned solar panels to polarotactic insects is unclear. Because fragmenting polarizing surfaces reduced their attractiveness, patch size may be a habitat-selection cue to aquatic insects, as has been observed in terrestrial and aquatic vertebrates (e.g., Herkert 1994; Funk et al. 2005; Moore et al. 2008). Another, more proximate, potential mechanism is that the low spatial resolution of the insect compound eye reduces polarization contrast, rendering the appearance of a white-gridded solar panel as less polarized and therefore less attractive than might be expected on the basis of our high-resolution polarization patterns. Although distinguishing between these two mechanisms is outside the scope of this paper, the possibility of a sensory origin rather than a more cognitive origin of the reduction in attractiveness facilitates mitigation of the ecological trap solar panels present.

The potential effects of polarized light pollution associated with solar panels on populations of aquatic insects remains unclear, but they are predicted to cause rapid and potentially large population declines (Delibes et al. 2001; Donovan & Thompson 2001), especially when located near natural wetlands and water bodies. The ubiquity of strong artificial polarizers in rural and urban environments has not been quantified. Until the population-scale effects of artificial polarizers on affected taxa are clarified, we urge caution in the placement of solar arrays and selection of panel design, particularly where rare or endangered species may be directly or indirectly affected. Solar farms, on which solar panels cover large areas, are rapidly increasing throughout Europe, Africa, and the United States. As artificial polarizers become a more common component of modern landscapes, intense selective pressure could trigger rapid evolution of novel habitat-selection cues (Kokko & Sutherland 2001). This possibility is contingent on the existence of other environmental signals that are tightly correlated with the presence of suitable water bodies. Because horizontally polarized light is the most reliable visual cue associated with water bodies under variable illumination conditions (Horváth & Varjú 2004), rapid evolution of cue use that facilitates evolutionary escape may be unlikely, especially if exploiting novel cues requires the evolution of new or enhanced sensory modalities.

Our results illustrate the attractiveness of highly and horizontally polarizing surfaces to polarotactic insects and show that both the degree and the direction of polarization of reflected light are important to mayflies, dolichopodids, Trichopterans, and tabanid flies in selecting among potential habitats. We also demonstrated that the increasing fragmentation of polarizing surfaces by a white grid reduces their attractiveness to polarotactic insects. This fact can be used to eliminate the trap effect associated with solar panels. By partitioning the active (i.e., highly and horizontally polarizing) surface of a panel into smaller subpanels with nonpolarizing (e.g., white) borders (Figs. 2 & 3), the surface is fragmented and becomes much less attractive. Substantial variation exists in the degree of partitioning associated with commercially manufactured solar cells and collectors and the width of the white panel partitions may determine whether adjacent panel sections are perceived as separate habitat patches or a single continuous patch. Although the relative effectiveness of partitioning solar panels appears taxon specific, the 10- to 26-fold reduction in attractiveness we found is biologically significant, which suggests partitioning will be an effective conservation measure for these and other polarotactic taxa. Because solar collectors and photovoltaic solar panels share polarization-relevant physical characteristics (i.e., they are smooth and dark colored), we expect polarized light pollution to be associated with solar collectors as well and that partitioning their surfaces with nonpolarizing strips should similarly reduce their attractiveness to polarotactic insects. New technologies such as three-dimensional solar cells that use vertically aligned arrays of carbon nanotubes (Camacho et al. 2007; Currie et al. 2008) reflect only a small amount of diffuse light with weak and not always horizontal polarization, and so should produce little polarized light pollution.

Ecological traps represent severe threats to animal populations (Delibes et al. 2001; Kokko & Sutherland 2001) and may contribute to ongoing declines of native species worldwide. Because ecological traps are predicted to arise from rapid environmental changes, including climate change, habitat fragmentation (Schlaepfer et al. 2002), and introductions of nonnative species (Schlaepfer et al. 2003), they are almost certainly more common than is recognized. Consequently, identifying methods to realign the attractiveness of habitats with their value for survival and reproduction is critical. Successful management of "behavioral landscapes" will require new conceptual approaches.

Acknowledgments

This work was supported by a grant (OTKA K-6846) from the Hungarian Science Foundation and funded in part by the Department of Energy Great Lakes Bioenergy Research Center (Office of Science BER DE-FC02-07ER64494). We are grateful for the donation of equipment from the German Alexander von Humboldt Foundation. We thank T. Getty and D. Hutto for their critical input. We also acknowledge the constructive comments of two anonymous reviewers.

Supporting Information

Color versions of Figs. 1–3, supplementary Figs. S1–S5, as well as supplementary Tables S1–S4 and their legends are available as part of the online article. The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

Bernáth, B., G. Szedenics, G. Kriska, and G. Horváth. 2001. Visual ecological impact of "shiny black anthropogenic products" on aquatic insects: oil reserviors and plastic sheets as polarized traps for insects associated with water. Archives of Nature Conservation and Landscape Research **40:**87–107.

Camacho, R. E., et al. 2007. Carbon nanotube arrays for photovoltaic applications. Journal of Minerals and Materials Society **59:**39–42.

Carrete, M., D. Serrano, J. C. Illera, L. P. Guillermo, M. Vögelli, A. Delgado, and J. L. Tella. 2009. Goats, birds, and emergent diseases: apparent and hidden effects of exotic species in an island environment. Ecological Applications **19:**840–853.

Collinge, S. K. 2000. Effects of grassland fragmentation on insect species loss, colonization, and movement patterns. Ecology **81:**2211–2226.

Csabai, Z., P. Boda, B. Bernáth, G. Kriska, and G. Horváth. 2006. A 'polarisation sun-dial' dictates the optimal time of day for dispersal by flying aquatic insects. Freshwater Biology **51:**1341–1350.

Currie, M. J., J. K. Mapel, T. D. Heidel, S. Goffri, and B. A. Baldo. 2008. High-efficiency organic solar concentrators for photovoltaics. Science **321:**226–228.

Delibes, M., P. Gaona, and P. Ferreras. 2001. Effects of an attractive sink leading into maladaptive habitat selection. The American Naturalist **158:**277–285.

Donovan, T. M., and F. R. Thompson. 2001. Modelling the ecological trap hypothesis: a habitat and demographic analysis for migrant songbirds. Ecological Applications **11:**871–882.

Dwernychuk, L. W., and D. A. Boag. 1972. Ducks nesting in association with gulls—an ecological trap? Canadian Journal of Zoology **50:**559–563.

Funk, W. C., A. E. Greene, P. S. Corn, and F. W. Allendorf. 2005. High dispersal in a frog species suggests that it is vulnerable to habitat fragmentation. Biology Letters **1:**13–16.

Hedin, J, G. Isacsson, M. Jonsell, and A. Komonen. 2008. Forest fuel piles as ecological traps for saproxylic beetles in oak. Scandanavian Journal of Forest Research **23:**348–357.

Herkert, J. R. 1994. The effects of habitat fragmentation on midwestern grassland bird communities. Ecological Applications **4:**461–471.

Horváth, G., and G. Kriska. 2008. Polarization vision in aquatic insects and ecological traps for polarotactic insects. Pages 204–229 in J. Lancaster and B. A. Briers, editors. Aquatic insects: challenges to populations. CAB International Publishing, Wallingford, United Kingdom.

Horváth, G., and D. Varjú. 1997. Polarization pattern of freshwater habitats recorded by video polarimetry in red, green and blue spectral ranges and its relevance for water detection by aquatic insects. Journal of Experimental Biology **200:**1155–1163.

Horváth, G., B. Bernáth, and G. Molnár. 1998. Dragonflies find crude oil visually more attractive than water: multiple-choice experiments on dragonfly polarotaxis. Naturwissenschaften **85:**292–297.

Horváth, G., and J. Zeil. 1996. Kuwait oil lakes as insect traps. Nature **379:**303–304.

Horváth, G., P. Malik, G. Kriska, and H. Wildermuth. 2007. Ecological traps for dragonflies in a cemetery: the attraction of *Sympetrum* species (Odonata: Libellulidae) by horizontally polarizing black gravestones. Freshwater Biology **52:**1700–1709.

Horváth, G., and D. Varjú. 2004. Polarized light in animal vision – polarization patterns in nature. Springer-Verlag, New York.

Horváth, G., G. Kriska, P. Malik, and B. A. Robertson. 2009. Polarized light pollution: a new kind of ecological photopollution. Frontiers in Ecology and the Environment **7:**317–325.

Jäch, M. A. 1997. Daytime swarming of rheophilic water beetles in Austria (Coleoptera: Elmidae, Hydraenidae, Haliplidae). Latissimus **9:**10–11.

Kokko, H., and W. J. Sutherland. 2001. Ecological traps in changing environments: ecological and evolutionary consequences of a behaviourally mediated Allee effect. Evolutionary Ecology Research **3:**537–551.

Kriska, G., G. Horváth, and S. Andrikovics. 1998. Why do mayflies lay their eggs en masse on dry asphalt roads? Waterimitating polarized light reflected from asphalt attracts Ephemeroptera. Journal of Experimental Biology **201:**2273–2286.

Kriska, G., P. Malik, I. Szivák, and G. Horváth. 2008. Glass buildings on river banks as "polarized light traps" for mass-swarming polarotactic caddis flies. Naturwissenschaften **95:**461–467.

Kriska, G., Z. Csabai, P. Boda, P. Malik, and G. Horváth. 2006. Why do red and dark-coloured cars lure aquatic insects? The attraction of water insects to car paintwork explained by reflection-polarization signals. Proceedings of the Royal Society B **273:**1667–1671.

Levins, R. 1968. Evolution in changing environments. Princeton University Press, Princeton, New Jersey.

Malik, P., R. Hegedüs, G. Kriska, and G. Horváth. 2008. Imaging polarimetry of glass buildings: why do vertical glass surfaces attract polarotactic insects? Applied Optics **47:**4361–4374.

Moore, R. P., W. D. Robinson, I. J. Lovette, and T. R. Robinson. 2008. Experimental evidence for extreme dispersal limitation in tropical forest birds. Ecology Letters **11:**960–968.

Nilsson, A. N. 1997. On flying *Hydroporus* and the attraction of *H. incognitus* to red car roofs. Latissimus **9:**12–16.

Resetarits, W., Jr., and C. A. Binckley. 2009. Spatial contagion of predation risk affects colonization dynamics in experimental aquatic landscapes. Ecology **90:**869–876.

Robertson, B. A., and R. L. Hutto. 2006. A framework for understanding ecological traps and an evaluation of existing evidence. Ecology **87:**1075–1085.

Robertson, B. A., and R. L. Hutto. 2007. Is selectively harvested forest an ecological trap for Olive-sided Flycatchers? Condor **109:**109–121.

Savolainen, E. 1978. Swarming in Ephemeroptera: the mechanism of swarming and the effects of illumination and weather. Annales Zoologici Fennici **15:**17–52.

Schlaepfer, M. A., M. C. Runge, and P. W. Sherman. 2002. Ecological and evolutionary traps. Trends in Ecology & Evolution **17:**478–480.

Schlaepfer, M. A., P. Sherman, B. Blossey, and M. C. Runge. 2003. Introduced species as evolutionary traps. Ecology Letters **8:**241–246.

Schwind, R. 1991. Polarization vision in water insects and insects living on a moist substrate. Journal of Comparative Physiology A **169:**531–540.

Schwind, R. 1995. Spectral regions in which aquatic insects see reflected polarized light. Journal of Comparative Physiology A **177:**439–448.

Vondel, B. J. van. 1998. Another case of water beetles landing on a red car roof. Latissimus **10:**29.

Watson, J. A. L. 1992. Oviposition by exophytic dragonflies on vehicles. Notulae Odonatologicae **3:**137.

Wildermuth, H. 1998. Dragonflies recognize the water of rendezvous and oviposition sites by horizontally polarized light: a behavioural field test. Naturwissenschaften **85:**297–302.

Wildermuth, H., and G. Horváth. 2005. Visual deception of a male Libellula depressa by the shiny surface of a parked car (Odonata: Libellulidae). International Journal of Odonatology **8:**97–105.