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How can horseflies be captured by solar panels? A new concept of tabanid traps using light polarization and electricity produced by photovoltaics

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ABSTRACT

Horseflies (Diptera: Tabanidae) can cause severe problems for humans and livestock because of the continuous annoyance performed and the diseases vectored by the haematophagous females. Therefore, effective horsefly traps are in large demand, especially for stock-breeders. To catch horseflies, several kinds of traps have been developed, many of them attracting these insects visually with the aid of a black ball. The recently discovered positive polarotaxis (attraction to horizontally polarized light) in several horsefly species can be used to design traps that capture female and male horseflies. The aim of this work is to present the concept of such a trap based on two novel principles: (1) the visual target of the trap is a horizontal solar panel (photovoltaics) attracting polarotactic horseflies by means of the highly and horizontally polarized light reflected from the photovoltaic surface. (2) The horseflies trying to touch or land on the photovoltaic trap surface are perished by the mechanical hit of a wire rotated quickly with an electromotor supplied by the photovoltaics-produced electricity. Thus, the photovoltaics is bifunctional: its horizontally polarized reflected light signal attracts water-seeking, polarotactic horseflies, and it produces the electricity necessary to rotate the wire. We describe here the concept and design of this new horsefly trap, the effectiveness of which was demonstrated in field experiments. The advantages and disadvantages of the trap are discussed. Using imaging polarimetry, we measured the reflection-polarization characteristics of the photovoltaic trap surface demonstrating the optical reason for the polarotactic attractiveness to horseflies.

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1. Introduction

Tabanid flies (Diptera: Tabanidae) can cause severe problems for humans and animals because of the diseases vectored by the haematophagous females (Foil, 1989; Luger, 1990; Hall et al., 1998; Sasaki, 2001; Lehane, 2005). Livestock, especially cattle and horses can be so strongly annoyed by the continuous attacks of blood-sucking tabanids that they cannot graze enough, and consequently their

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meat and milk production is drastically reduced (Hunter and Moorhouse, 1976; Harris et al., 1987; Lehane, 2005). Furthermore, tabanid bites cause visible scars on the skin of host animals. The bigger the scarless area of cattle hides, for example, the higher their value. As a consequence, the numerous bites of blood-sucking female tabanids can drastically lower the value of cattle bred for hide. Therefore, effective tabanid traps are in large demand, especially for stock-breeders.

Historically, traps based on flight interception principles and attraction to large black targets have been routinely used to capture tabanids (Malaise, 1937; Gressitt and Gressitt, 1962; Catts, 1970; Chvala et al., 1972; von Kniepert, 1979; Wall and Doane, 1980; Hribar et al., 1992). Blue-black cloth traps, such as the Nzi trap (Mihok, 2002; van Hennekeler et al., 2008; Mihok and Lange, in press), for example, which rely on different attraction principles, are also frequently used for trapping tabanids. A common feature of many tabanid traps is that they are composed of a visual target – most frequently a black sphere – suspended underneath a tent-like canopy. The function of the visual target is to attract tabanids from a remote distance by means of optical cues (intensity and colour of target-reflected light, shape and motion of the target). When the attracted female tabanids land on the target and experience that a potential blood meal is not available, a proportion of them fly upward into the funnel-like end of the canopy, where they are trapped by a glass or plastic container. These traps capture almost exclusively female tabanids that look for host animals to suck their blood (Lehane, 2005).

Horváth et al. (2008, 2010a) showed that male and female tabanids are attracted to horizontally polarized light, just like many other aquatic insect species (Schwind, 1991, 1995; Wildermuth, 1998, 2007; Horváth and Varjú, 2004; Csabai et al., 2006; Kriska et al., 2006, 2007, 2008, 2009; Horváth and Kriska, 2008; Lerner et al., 2008; Malik et al., 2008; Horváth et al., 2009). The reason for this adaptive behaviour is that tabanids lay their eggs onto marsh plants near freshwater bodies or mud, thus they have to find water, what is performed by means of the horizontal polarization of light reflected from the water surface. It has been suggested that this positive polarotactic behaviour in tabanids could be used to develop new tabanid traps (Horváth et al., 2008).

The aim of this work is to present the concept of such a trap based on two novel principles: (1) in this trap the new visual target is a horizontal solar panel (photovoltaics) that attracts polarotactic tabanids by means of the highly and horizontally polarized light reflected from the photovoltaic surface. (2) The tabanids trying to touch or land on the photovoltaics are perished by the mechanical hit of a wire rotated quickly with an electromotor supplied by the photovoltaics-produced electricity. We describe here the concept and design of this new tabanid trap, the effectiveness of which was demonstrated in field experiments. We discuss the advantages and disadvantages of the new trap. Using imaging polarimetry, we measured the reflection-polarization characteristics of the photovoltaic trap surface showing the optical reason for the polarotactic attractiveness to tabanids. Our study demonstrates how basic scientific knowledge, i.e. the positive polarotaxis in

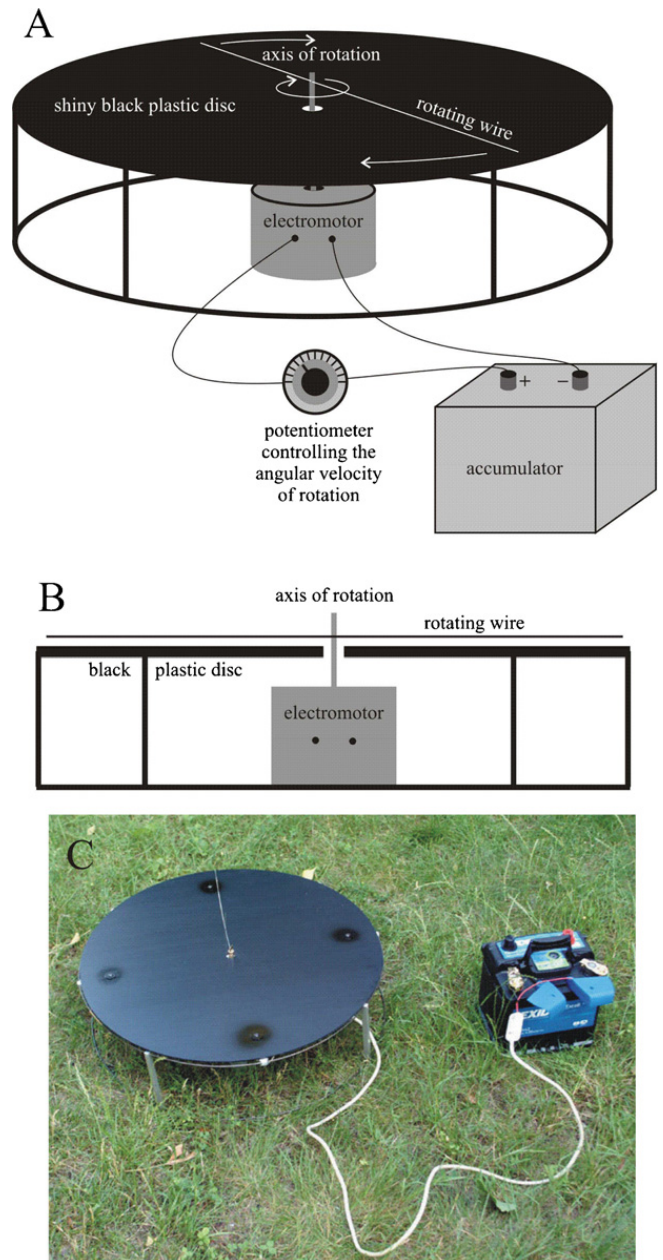


Fig. 1. (A) Schematic structure of tabanid trap 1 used in experiment 1. (B) Cross section of the trap. (C) Photograph of the trap in the field.

tabanids, can be applied in the design of a new tabanid trap.

2. Materials and methods

Tabanid trap 1 was composed of a horizontal, circular, shiny, black, plastic board (radius = 30 cm, thickness = 5 mm) fixed onto a cylindrical aluminium frame of height 15 cm and radius 25 cm (Fig. 1). Below the black board an electromotor (Igarashi sp3650-65g, Conrad Electronic, Budapest) was fixed to the aluminium frame in such a way that its vertical axis of rotation got through the center of the horizontal black board. At its center a thin (thickness = 0.5 mm), 60 cm long metal wire was fixed to the vertical axis of rotation. Thus, the wire could rotate around its center in a horizontal plane, parallel to and 3 cm



Fig. 2. (A) Photograph of trap 2 used in experiments 2–4. Right: the trap composed of two horizontal solar panels and a wire rotating above the photovoltaic surface. Left: two supplementary solar panels with a tilted surface. (B–E) Photographs of tabanid flies landed on the horizontal photovoltaic surface of trap 2.

above the surface of the black board. The electromotor was driven by a car battery (45 Ah, lead-acid type) supplying a direct voltage of 12 V. The direct current to the electromotor was controlled by a common potentiometer, with which the angular velocity of the rotating axis of the electromotor could be adjusted.

Tabanid trap 2 was composed of two rectangular (30 cm × 60 cm) horizontal solar panels (Omnitron F 10/12, Conrad Electronic, Budapest) fixed to the top of an aluminium house (60 cm × 60 cm × 20 cm). At the center of the horizontal square (60 cm × 60 cm) surface of the trap the vertical axis of rotation of an electromotor (Igarashi sp3650-65 g, Conrad Electronic, Budapest) got through an aluminium band (1 cm × 2 cm × 60 cm). To the cylindrical (diameter = 2 cm, height = 1 cm) aluminium head of this rotation axis a thin (thickness = 0.5 mm), 60 cm long metal wire was fixed in such a way that the wire could rotate horizontally around its center and parallel to and 3 cm above the photovoltaic trap surface. The aluminium band between the two photovoltaics and their aluminium frames were sprayed by a black paint. Thus, the whole horizontal surface of the trap was shiny black (Fig. 2A) and reflected highly (i.e. with high degrees of polarization) and horizontally polarized light to attract polarotactic tabanids. The electromotor was supplied through a controlling electronics by the direct current produced by the two solar panels. This electronics ensured, for example, that after its switch on the rotating wire can reach gradually its maximal angular velocity. Without such a slow spinning up,

the wire could coil onto the rotation axis of the electromotor. After its switch off the rotation of the motor's axis ceased promptly, because at spinning off the wire does not coil onto the rotation axis. At full sunshine and at higher

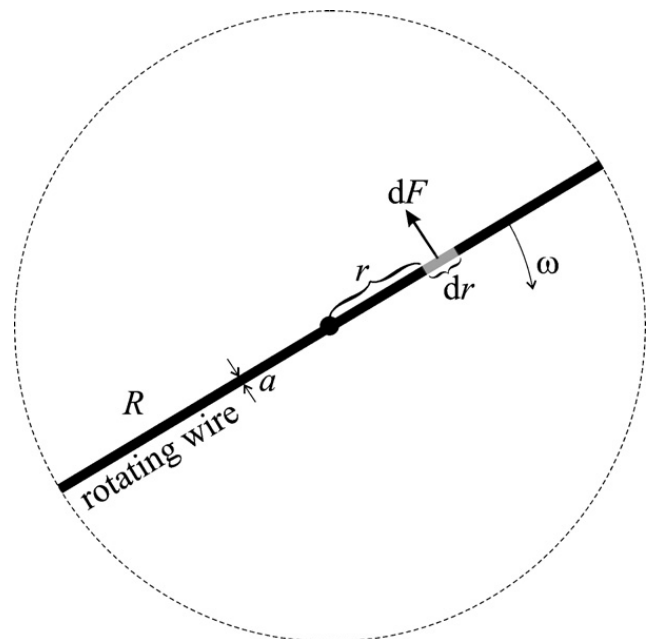


Fig. 3. Drawing for calculation of the power P needed to rotate a wire of length $2R$ and thickness a with an angular velocity ω , if the wire is fixed to the axis of rotation at its center.

solar elevation angles ($>29^\circ$) above the horizon the direct current produced by the two horizontal solar panels could rotate the wire with large enough angular velocities to perish all tabanid flies attracted to the horizontally polarizing photovoltaic trap surface hitting them mechanically by the wire. When the solar elevation angle was lower than about 29° , two additional solar panels (Omnitron F 10/12, Fig. 2A) were necessary to rotate the wire with high enough angular velocities to capture tabanids. The aluminium frame of these additional photovoltaics was not painted black, because the functions of the supplementary solar panels was to produce enough direct current for the electromotor rotating the wire, rather than to attract tabanids. Horváth et al. (2010b) showed that strongly polarizing shiny black surfaces with an appropriate white frame and grid lose their attractiveness to polarotactic insects, including tabanids.

Calculation of the power needed to rotate the wire of the tabanid trap. Consider a $2R$ long wire with thickness a fixed at its center perpendicular to a vertical axis of rotation. Let the wire rotate in a horizontal plane with an angular velocity ω . Consider an elementary length dr of the wire placed at distance r from the rotation axis (Fig. 3). The tangential velocity of this elementary part is $r\omega$. The elementary drag force acting to this elementary wire section is

$$dF = \frac{1}{2} k \rho (a \cdot dr) (r\omega)^2 = \frac{1}{2} k \rho a \omega^2 r^2 \cdot dr, \quad (1)$$

where ρ is the air density, and k is the shape coefficient of drag (being equal to the shape coefficient of a cylinder, if the wire has a circular cross section). The elementary torque of the elementary drag force dF acting to the elementary wire section dr with respect to the axis of rotation is:

$$dM = r \cdot dF = \frac{1}{2} k \rho a \omega^2 r^3 \cdot dr. \quad (2)$$

The elementary work done by the elementary drag force dF along an elementary arc $ds = r \cdot d\varphi$ is:

$$dW = dF \cdot ds = dF \cdot r \cdot d\varphi = (dF \cdot r) \cdot \omega \cdot dt = dM \cdot \omega \cdot dt. \quad (3)$$

The elementary power needed to rotate the elementary wire section dr with an angular velocity ω is:

$$dP = \frac{dW}{dt} = \omega \cdot dM = \frac{1}{2} k \rho a \omega^3 r^3 \cdot dr. \quad (4)$$

This elementary power dP is necessary to compensate the elementary torque dM of the elementary drag force dF . The total power P needed to compensate the full torque M of drag acting to the wire rotating with an angular velocity ω is obtained if the elementary powers dP are summed, that is integrated along the whole length $2R$ of the wire:

$$P = 2 \int_{r=0}^{r=R} dP = 2 \int_{r=0}^{r=R} \frac{1}{2} k \rho a \omega^3 r^3 \cdot dr = k \rho a \omega^3 \left[\frac{r^4}{4} \right]_0^R = \frac{k \rho a \omega^3 R^4}{4}. \quad (5)$$

Experiment 1 was performed between 12 and 30 July 2009 on five days near a Hungarian horse farm at Szokolya ($47^\circ 52'N$, $19^\circ 00'E$). The aim of this experiment was to test whether (i) the movement of the wire of tabanid trap 1,

and (ii) the buzz and/or the air motion produced by the rotating wire can or cannot disturb and thus repel tabanids attracted to the horizontally polarizing trap surface. During this experiment the weather was sunny and warm, thus flying tabanids were abundant in the air around trap 1 laid on the grassy ground.

Every day experiment 1 lasted from 10:00 h to 15:30 h (local summer time = UTC + 2 h), during which the wire of trap 1 was still for 30 min, then it was rotating for 30 min, and this was repeated four times. After a 30-min rotation the trap surface was cleaned by 70% ethanol from the droplets of tabanid body fluid and eggs sometimes arisen when tabanids were hit by the rotating wire. When the wire was still, we observed and counted the following two typical reactions of tabanid flies approaching the horizontal shiny black surface of trap 1: T, touching the trap surface. In nature this is a typical reaction of tabanids when they touch the water surface to drink or bath in order to cool their heated-up body. L, landing (and occasionally walking) on the trap surface. Tabanids neither land nor walk on the water surface. These are their typical reactions on highly and horizontally polarizing artificial surfaces (Horváth and Kriska, 2008; Horváth et al., 2008, 2009, 2010a,b). In spite of the quick rotation of the wire, a few tabanids were able to touch or land on the trap surface. Then we counted the following tabanid-specific reactions: T and L (as earlier). H, hitting the tabanid trying to touch or land on the trap surface by the rotating wire. When a flying tabanid was hit, the wire produced a typical twanging sound, by which reaction H could be heard and counted by the observer. During the experiment we collected several carcasses of tabanids hit by the rotating wire and thrown away on the grassy ground.

As mentioned, at still wire the reactions of tabanids were T and L. Then, if the wire had been rotated, it could have hit and perished tabanids when they touched or landed on the trap surface. Let N_T^{still} and N_L^{still} be the number of tabanids touching (T) and landing (L) on the trap surface, respectively, during the time period when the wire was still. If the wire had been rotated and its rotation had not been disturbed and repelled tabanids attracted to the horizontally polarized light reflected from the trap surface, the rotating wire could have perished $N_T^{\text{rotating}} + N_L^{\text{rotating}}$ tabanids. Let N_H^{rotating} , N_T^{rotating} and N_L^{rotating} be the number of tabanids hit (H) by the rotating wire, or touching (T) and landing (L) on the trap surface, respectively, during the time period when the wire was rotating (this time period was the same as the period when the wire was still). If the motion of the wire and/or the buzz and/or the air motion produced by the rotating wire disturbed and thus repelled the visually attracted tabanids, then $N_H^{\text{rotating}} + N_T^{\text{rotating}} + N_L^{\text{rotating}} < N_T^{\text{still}} + N_L^{\text{still}}$ could be expected. Thus, we define the following measure of disturbance of trap 1 due to the wire rotation:

$$Q_{\text{disturbance}} = 1 - \frac{(N_T^{\text{rotating}} + N_L^{\text{rotating}} + N_H^{\text{rotating}})}{N_T^{\text{still}} + N_L^{\text{still}}}. \quad (6)$$

If the rotation of the wire disturbed and thus repelled all polarotactically attracted tabanids (that is $N_T^{\text{rotating}} + N_L^{\text{rotating}} + N_H^{\text{rotating}} = 0$), then $Q_{\text{disturbance}} = 1$ (100%), while

if the wire rotation were not repellent at all (i.e. $N_T^{\text{rotating}} + N_L^{\text{rotating}} + N_H^{\text{rotating}} = N_T^{\text{still}} + N_L^{\text{still}}$), then $Q_{\text{disturbance}} = 0$ (0%). Since we had only one exemplar of trap 1, N_T^{still} and N_L^{still} , furthermore N_H^{rotating} , N_T^{rotating} and N_L^{rotating} could be measured only subsequently, rather than simultaneously. Using 30 min as the unit period of rotation and stillness of the wire, we tried to minimize the inevitable influence of the temporal variation of tabanid abundance in the air near trap 1 during each session of experiment 1.

Experiment 2 was done on 11 and 12 July 2010 at the same site as experiment 1. The aim of experiment 2 was to test whether the wire of tabanid trap 2 can be rotated with the use of the electricity produced by a horizontal photovoltaic area of 60 cm × 60 cm with large enough angular velocities to perish all tabanids touching the horizontally polarizing photovoltaic trap surface. During this experiment the weather was sunny and warm, thus flying tabanids were abundant in the air around trap 2 laid on the grassy ground. The procedure of experiment 1 was repeated with the use of trap 2. The disturbance $Q_{\text{disturbance}} = 1 - (N_T^{\text{rotating}} + N_L^{\text{rotating}} + N_H^{\text{rotating}}) / (N_T^{\text{still}} + N_L^{\text{still}})$ of trap 2 due to the rotation of its wire was again calculated.

Experiment 3 was performed between 13 and 17 July 2010 at the site as experiment 1. The aim of experiment 3 was to test the functioning of tabanid trap 2 and to measure its tabanid-capturing efficiency Q_{capture} without a supplementary solar panel. During this experiment the weather was sunny and warm, thus flying tabanids were abundant in the air around trap 2 laid on the grassy ground. A session of experiment 3 lasted every day from 10:00 h to 17:30 h (UTC + 2 h). During a session the wire of trap 2 was rotating continuously for 7.5 h. In spite of the wire rotation, a few tabanids were able to touch or land on the photovoltaic trap surface. After each day the trap surface was cleaned by 70% ethanol from the body fluid and eggs of hit tabanids. As in experiments 1 and 2, we counted the following reactions of tabanids approaching trap 2: H, hitting; T, touching; and L, landing on the horizontal photovoltaic trap surface. The tabanid-capturing efficiency of trap 2 is defined as

$$Q_{\text{capture}} = \frac{N_H^{\text{rotating}}}{N_H^{\text{rotating}} + N_T^{\text{rotating}} + N_L^{\text{rotating}}}, \quad (7)$$

where N_H^{rotating} , N_T^{rotating} and N_L^{rotating} are the numbers of reactions H, T and L, respectively, when the wire was rotating (throughout experiment 3).

Experiment 4 was conducted between 2 and 6 August 2010 at the same site as experiment 1. The aim of experiment 4 was to test whether a supplementary solar panel can enhance the time period when trap 2 functions efficiently. During this experiment the weather was sunny and warm, thus flying tabanids were abundant in the air around trap 2 laid on the grassy ground. A session of experiment 4 lasted every day from 09:00 h to 19:00 h (UTC + 2 h). During a session the wire of trap 2 was rotating continuously for 10 h. Apart from the horizontal photovoltaic surface of trap 2, we used an additional photovoltaic surface (60 cm × 60 cm) composed of two solar panels (Omni-tron

F 10/12, 30 cm × 60 cm). The supplementary photovoltaic surface was tilted at 45° from the horizontal. In order to maximize the sunlight-collecting efficiency of this supplementary photovoltaics, its symmetry axis was oriented hourly toward the azimuth direction of the sun moving along its arc on the sky. After each day the photovoltaic trap surfaces were cleaned by 70% ethanol. As in experiments 1–3, we counted the following reactions of tabanids approaching trap 2: H, hitting; T, touching; and L, landing on the horizontal photovoltaic trap surface. Tabanids never touched or landed on the oblique surface of the supplementary photovoltaics. The tabanid-capturing efficiency $Q_{\text{capture}} = N_H^{\text{rotating}} / (N_H^{\text{rotating}} + N_T^{\text{rotating}} + N_L^{\text{rotating}})$ of trap 2 was calculated.

The reflection-polarization characteristics of both tabanid traps were measured by imaging polarimetry in the red (650 ± 40 nm = wavelength of maximal sensitivity ± half bandwidth of the CCD detectors of the polarimeter), green (550 ± 40 nm) and blue (450 ± 40 nm) parts of the spectrum. The method of imaging polarimetry has been described in detail by Horváth and Varjú (2004). The polarimetric measurements were performed in sunshine, under clear skies.

3. Results

According to Eq. (5), the power P needed to rotate a 2R long wire is proportional to the air density ρ , the wire thickness a , the 3rd power of the angular velocity ω , and the 4th power of the half length R . The area of the solar panel necessary to rotate the wire with a given angular velocity ω can be calculated from (Eq. (5)), from which the following conclusions can be drawn: (i) If the thickness a of a wire is doubled, for example, the rotation of the wire with the same angular velocity ω needs twice as large power (photovoltaic area). (ii) To rotate a wire with a double ω is possible by a $2^3 = 8$ -times larger power (photovoltaic area). (iii) If the length of a wire is doubled, its rotation with the same ω requires a $2^4 = 16$ -times greater power (photovoltaic area).

Fig. 4 shows the reflection-polarization characteristics of the surface of trap 1 used in experiment 1 measured by imaging polarimetry in the red, green and blue parts of the spectrum. The degree of polarization d reflected from the horizontal trap surface was almost 100% (represented by black shade in the d -patterns), because the plastic surface was shiny black and the measurement happened from the Brewster angle $\theta_{\text{Brewster}} = \arctan(n) = 56.3^\circ$ from the vertical (i.e. 33.7° from the horizontal), where $n = 1.5$ is the refractive index of plastic. The angle of polarization of reflected light was $\alpha \approx 90^\circ$ from the vertical, meaning horizontal polarization (represented by bright green and blue colours in the α -patterns). Thus, the horizontal, shiny, black surface of trap 1 reflected highly (high d -values) and horizontally ($\alpha \approx 90^\circ$) polarized light, which attracted polarotactic tabanids. This was the reason for the large attractiveness of the trap surface to tabanid flies. All these polarization characteristics were practically independent of the wavelength of light, because the trap surface was colourless (black).

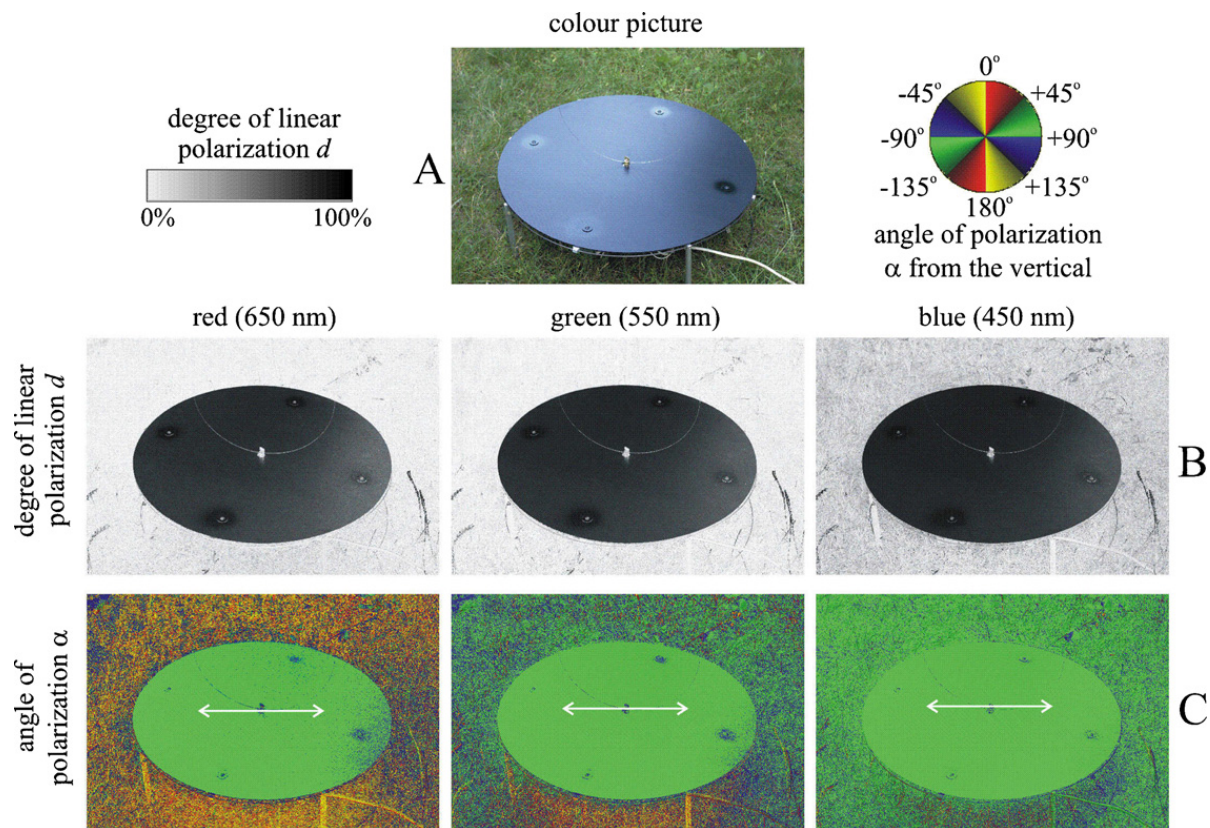


Fig. 4. Colour picture (A) and patterns of the degree of polarization d (B) and angle of polarization α (C) of the tabanid trap 1 used in experiment 1 measured by imaging polarimetry in the red (650 nm), green (550 nm) and blue (450 nm) parts of the spectrum. The double headed arrows in the α -patterns show the direction of polarization of light reflected from the trap surface. The angle of elevation of the optical axis of the polarimeter was -34° from the horizontal (Brewster angle). The horizontal shiny black circular surface of the trap was in shade and illuminated by skylight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Rows 1–3 in Fig. 5 show photographs of the carcasses of tabanid flies hit by the rotating wire of trap 1 in experiment 1. It is clear from these pictures and on the basis of our observations that the tabanids hit by the rotating wire suffered so serious injuries that they inevitably perished sooner or later. From these carcasses we revealed that both sexes (females and males) of tabanids were attracted and perished by trap 1. This demonstrates well the tabanid-perishing efficiency of this new technique.

According to Table 1, in experiment 1 the disturbance $Q_{\text{disturbance}}$ due to the wire rotation of trap 1 changed between 4.8% and 9.1% with an average of 6.7%. Note, however, that the calculated values of $Q_{\text{disturbance}}$ were partly influenced by the inevitable temporal variation of the abundance of tabanid flies in the air near trap 1, since counting the number of tabanid reactions to the trap in the subsequent periods of still and rotating wire happened subsequently. Consequently, the calculated disturbance is only an estimation of the real disturbance.

From experiment 1 we concluded that (i) the motion of the wire and/or the buzz and/or the air motion induced by the rotating wire of trap 1 repelled less than about 7% of tabanids attracted to the horizontally polarizing trap surface, and (ii) the rotating wire could hit the attracted tabanids so strongly that they perished. Consequently, it was worth building an improved version of trap 1. Thus, we built trap 2, in which the electromotor, rotating the wire, was supplied with the electricity produced by

photovoltaics, the horizontal shiny black surface of which served as a horizontally polarizing and thus tabanid-attracting reflector.

Rows 4–7 in Fig. 5 show photographs of the carcasses of tabanids hit by the rotating wire of trap 2 in experiment 2. Both female and male tabanids (*Tabanus bovinus*, *Tabanus tergstinus*, *Tabanus quatuornotatus*, *Tabanus bromius*, *Tabanus miki*, *Haematopota pluvialis*, *Haematopota pluvialis*, *Silvius vituli*) hit suffered again so strong injuries that they perished. According to Table 2, in experiment 2 the disturbance of $Q_{\text{disturbance}}$ due to the wire rotation of trap 2 was 4.2% and 7.3% with an average of 5.6%.

From experiment 2 we concluded that (i) the motion of the wire and/or the buzz and/or the air motion induced by the rotating wire of trap 2 repelled less than about 6% of tabanids attracted to the horizontally polarizing horizontal photovoltaic trap surface, and (ii) the rotating wire could hit the attracted tabanids so that they perished.

Figs. 6 and 7 show the reflection-polarization characteristics of the horizontal photovoltaic surface of trap 2 and the oblique supplementary photovoltaics used in experiments 2–4 measured by imaging polarimetry in the red, green and blue parts of the spectrum from two different azimuthal directions of view. The degree of polarization d reflected from the horizontal photovoltaic trap surface was approximately 100% and the direction of polarization of reflected light was horizontal ($\alpha \approx 90^\circ$ from the vertical) at the Brewster angle (-34° from the horizontal).

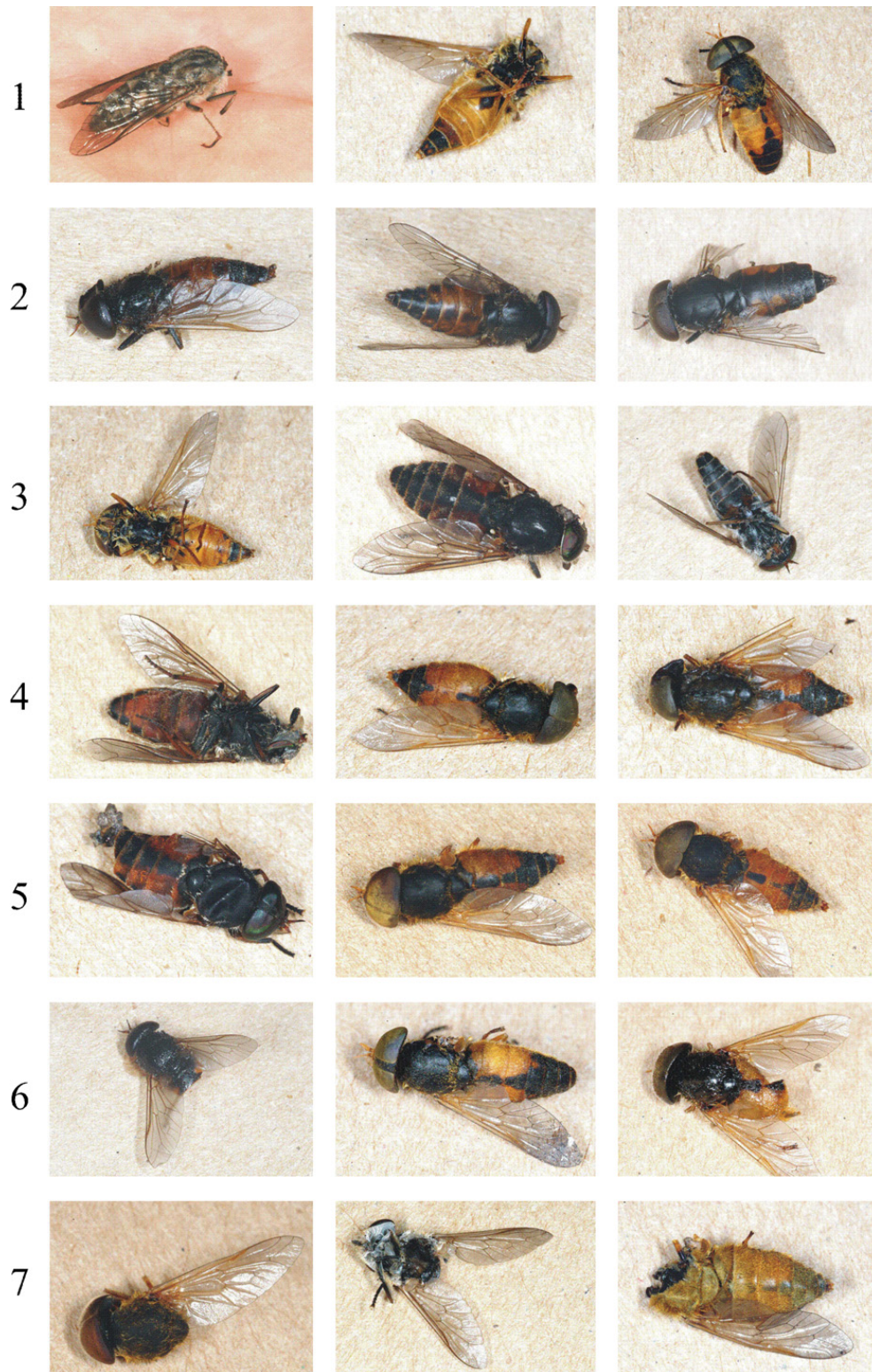


Fig. 5. Photographs of the carcasses of tabanid flies hit by the rotating wire in experiment 1 (rows 1–3) and experiment 2 (rows 4–7).

Thus, the horizontal, shiny, black photovoltaic trap surface reflected highly and horizontally polarized light, which was strongly attractive to polarotactic tabanids. This was the reason for the large attractiveness of the horizontal photovoltaic trap surface to tabanid flies. On the other hand, depending on the azimuthal direction of view, the tilted supplementary photovoltaic surface reflected light

with moderate degrees of polarization ($d < 25\%$) and with not always horizontal, but also with tilted directions of polarization. Consequently, this supplementary photovoltaics was unattractive to polarotactic tabanids. This unattractiveness to tabanids was further enhanced by the fact that the supplementary solar panels had a bright frame, that repelled polarotactic insects (Horváth et al.,

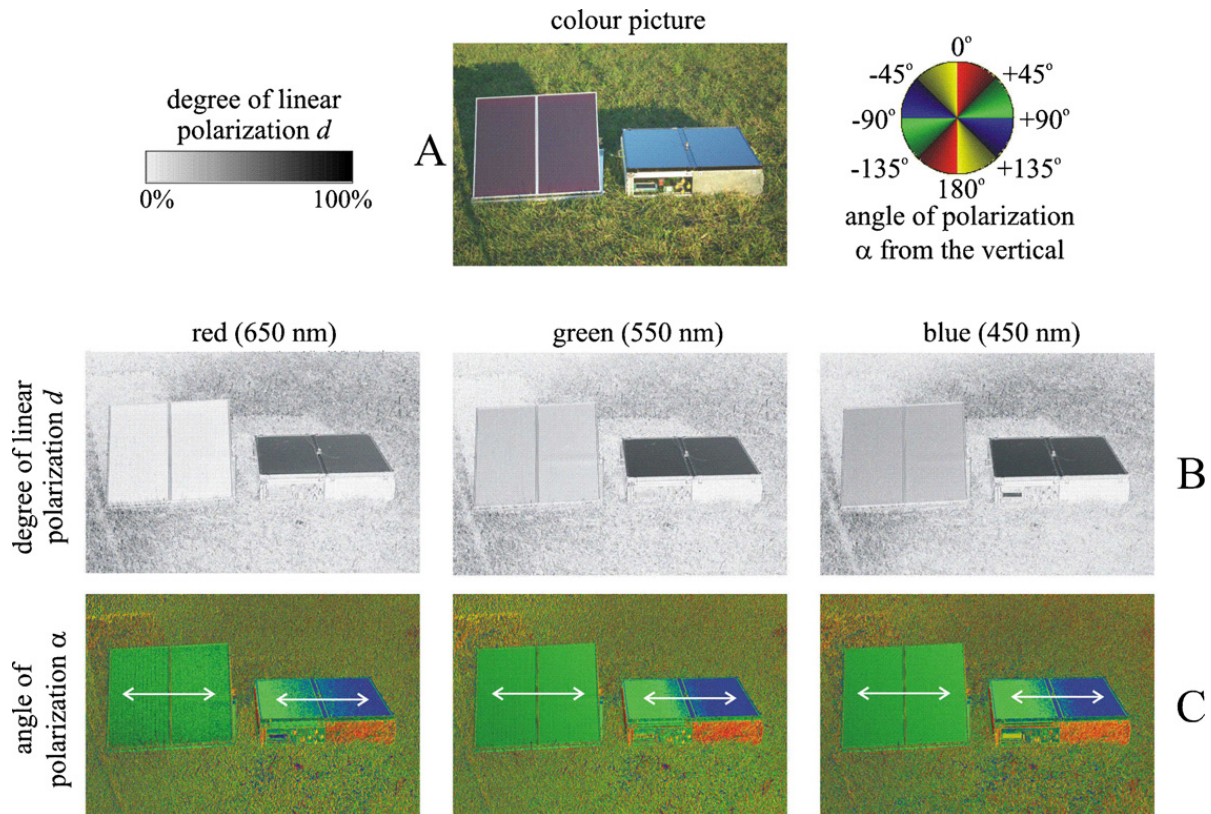


Fig. 6. Colour picture (A) and patterns of the degree of polarization d (B) and angle of polarization α (C) of the tabanid trap 2 and its supplementary tilted photovoltaics used in experiments 2–4 measured by imaging polarimetry in the red (650 nm), green (550 nm) and blue (450 nm) parts of the spectrum. The double headed arrows in the α -patterns show the local directions of polarization of light reflected from the photovoltaic surfaces. The angle of elevation of the optical axis of the polarimeter was -34° from the horizontal (Brewster angle). The photovoltaics were illuminated by skylight and sunlight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

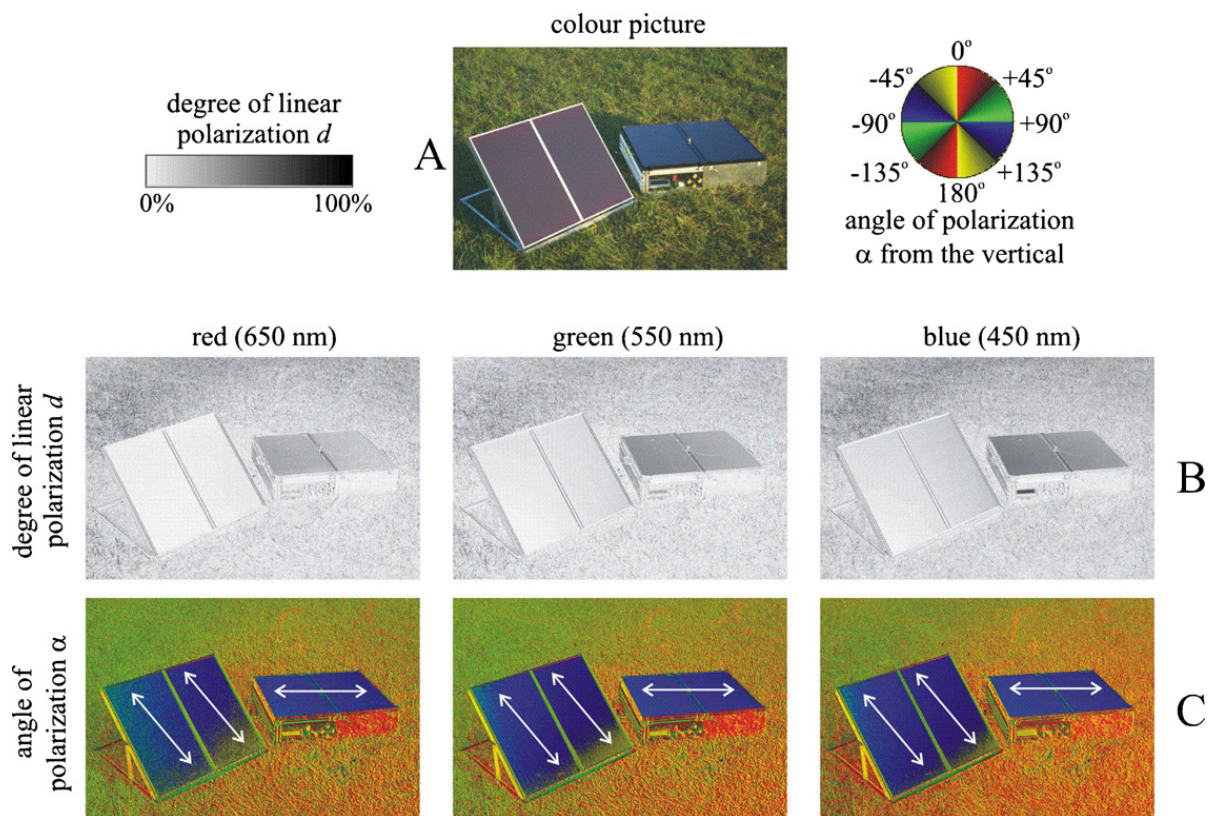


Fig. 7. As Fig. 6 for an oblique azimuthal direction of view.

Table 1

Number of reactions of tabanid flies N_T^{still} , N_L^{still} , N_H^{rotating} , N_T^{rotating} , N_L^{rotating} and the disturbance $Q_{\text{disturbance}} = 1 - (N_T^{\text{rotating}} + N_L^{\text{rotating}} + N_H^{\text{rotating}}) / (N_T^{\text{still}} + N_L^{\text{still}})$ of trap 1 due to the rotation of its wire in experiment 1. T, touching the horizontal shiny black surface of trap 1; L, landing (and occasionally walking) on the trap surface; H, hitting the tabanid trying to touch or land on the trap surface by a rotating wire.

Wire was still		Wire was rotating	
Time (UTC + 2 h)	Reactions of tabanids	Time (UTC + 2 h)	Reactions of tabanids
12 July 2009			
10:00–10:30	25 T + 15 L	10:30–11:00	1 T + 0 L + 21 H
11:00–11:30	11 T + 10 L	11:30–12:30	2 T + 1 L + 26 H
12:30–13:00	15 T + 13 L	13:00–13:30	0 T + 0 L + 34 H
13:30–14:00	22 T + 17 L	14:00–14:30	2 T + 2 L + 31 H
14:30–15:00	13 T + 5 L	15:00–15:30	1 T + 0 L + 18 H
Sum	86 T + 60 L	Sum	6 T + 3 L + 130 H
$Q_{\text{disturbance}}$		4.8%	
17 July 2009			
10:00–10:30	21 T + 19 L	10:30–11:00	0 T + 1 L + 12 H
11:00–11:30	6 T + 2 L	11:30–12:30	2 T + 0 L + 23 H
12:30–13:00	17 T + 13 L	13:00–13:30	1 T + 0 L + 27 H
13:30–14:00	12 T + 9 L	14:00–14:30	1 T + 1 L + 24 H
14:30–15:00	5 T + 2 L	15:00–15:30	1 T + 0 L + 4 H
Sum	61 T + 45 L	Sum	5 T + 2 L + 90 H
$Q_{\text{disturbance}}$		8.5%	
21 July 2009			
10:00–10:30	14 T + 8 L	10:30–11:00	0 T + 0 L + 19 H
11:00–11:30	31 T + 5 L	11:30–12:30	1 T + 0 L + 14 H
12:30–13:00	14 T + 11 L	13:00–13:30	1 T + 3 L + 35 H
13:30–14:00	10 T + 8 L	14:00–14:30	2 T + 0 L + 26 H
14:30–15:00	24 T + 7 L	15:00–15:30	1 T + 1 L + 17 H
Sum	93 T + 39 L	Sum	5 T + 4 L + 111 H
$Q_{\text{disturbance}}$		9.1%	
23 July 2009			
10:00–10:30	23 T + 10 L	10:30–11:00	1 T + 1 L + 10 H
11:00–11:30	20 T + 15 L	11:30–12:30	2 T + 0 L + 26 H
12:30–13:00	9 T + 16 L	13:00–13:30	0 T + 2 L + 25 H
13:30–14:00	5 T + 3 L	14:00–14:30	1 T + 0 L + 22 H
14:30–15:00	7 T + 2 L	15:00–15:30	2 T + 1 L + 10 H
Sum	64 T + 46 L	Sum	6 T + 4 L + 93 H
$Q_{\text{disturbance}}$		6.4%	
30 July 2009			
10:00–10:30	22 T + 16 L	10:30–11:00	1 T + 1 L + 35 H
11:00–11:30	33 T + 26 L	11:30–12:30	2 T + 1 L + 77 H
12:30–13:00	60 T + 54 L	13:00–13:30	3 T + 0 L + 65 H
13:30–14:00	41 T + 39 L	14:00–14:30	2 T + 1 L + 61 H
14:30–15:00	16 T + 14 L	15:00–15:30	2 T + 0 L + 50 H
Sum	172 T + 149 L	Sum	10 T + 3 L + 288 H
$Q_{\text{disturbance}}$		6.2%	
Total	476 T + 339 L	Total	32 T + 16 L + 712 H
Averaged $Q_{\text{disturbance}}$		6.7%	

2010b). All these polarization characteristics were practically independent of the wavelength of light, because the photovoltaic surfaces were colourless (black).

Table 3 shows the number of tabanid reactions and the tabanid-capturing efficiency Q_{capture} of trap 2 in experiment 3, when the wire was rotating continuously without a supplementary solar panel. We experienced that in full sunshine trap 2 functioned excellently: from 10:00 to 17:30 h (UTC+2 h) – during which the solar elevation angle changed between its minima and maxima as given in Table 3 – the wire was rotating continuously with large enough angular velocities to hit and perish almost all tabanid flies trying to touch or land on the horizontal photovoltaic trap surface. Q_{capture} of trap 2 changed between 89.4% and 94.3% with an average of 91.5%. The

tabanid-capturing efficiency was not 100%, because a few tabanids could touch or land on the photovoltaic trap surface in spite of the fact that the wire was rotating.

From experiment 3 we concluded that if the solar elevation angle was not lower than about 29° (Table 3), trap 2 functioned well in full sunshine and it could capture tabanid flies attracted to its horizontal photovoltaic surface with an efficiency of about 92%. The tabanids that escaped from the rotating wire after touching or landing on and flying away from the photovoltaic trap surface could perish when they returned later to the trap. We observed that some tabanids landing on the photovoltaics were hit by the rotating wire when later they tried to fly away. Thus, the 92% tabanid-capturing efficiency is an under-estimation.

Table 2

Number of reactions of tabanid flies N_T^{still} , N_L^{still} , N_T^{rotating} , N_L^{rotating} , N_H^{rotating} and the disturbance $Q_{\text{disturbance}} = 1 - (N_T^{\text{rotating}} + N_L^{\text{rotating}} + N_H^{\text{rotating}}) / (N_T^{\text{still}} + N_L^{\text{still}})$ of trap 2 due to the rotation of its wire in experiment 2. T, touching the horizontal shiny black photovoltaic surface of trap 2; L, landing on the photovoltaic trap surface; H, hitting the tabanid trying to touch or land on the photovoltaic trap surface by a rotating wire.

Wire was still		Wire was rotating	
Time (UTC + 2 h)	Reactions of tabanids	Time (UTC + 2 h)	Reactions of tabanids
11 July 2010			
10:00–10:30	21 T + 10 L	10:30–11:00	1 T + 1 L + 24 H
11:00–11:30	13 T + 9 L	11:30–12:30	1 T + 1 L + 26 H
12:30–13:00	17 T + 12 L	13:00–13:30	2 T + 1 L + 27 H
13:30–14:00	20 T + 15 L	14:00–14:30	1 T + 1 L + 23 H
14:30–15:00	18 T + 7 L	15:00–15:30	2 T + 1 L + 24 H
Sum	89 T + 53 L	Sum	7 T + 5 L + 124 H
$Q_{\text{disturbance}}$		4.2%	
12 July 2010			
10:00–10:30	12 T + 11 L	10:30–11:00	1 T + 0 L + 15 H
11:00–11:30	16 T + 5 L	11:30–12:30	1 T + 1 L + 22 H
12:30–13:00	11 T + 9 L	13:00–13:30	1 T + 1 L + 22 H
13:30–14:00	17 T + 11 L	14:00–14:30	2 T + 0 L + 16 H
14:30–15:00	14 T + 4 L	15:00–15:30	1 T + 1 L + 18 H
Sum	70 T + 40 L	Sum	6 T + 3 L + 93 H
$Q_{\text{disturbance}}$		7.3%	
Total	159 T + 93 L	Total	13 T + 8 L + 217 H
Averaged $Q_{\text{disturbance}}$	5.6%		

Table 3

Number of reactions of tabanid flies N_T^{rotating} , N_L^{rotating} , N_H^{rotating} and the tabanid-capturing efficiency $Q_{\text{capture}} = N_H^{\text{rotating}} / (N_H^{\text{rotating}} + N_T^{\text{rotating}} + N_L^{\text{rotating}})$ of trap 2 in experiment 3, when the wire was rotating continuously without a supplementary solar panel. T, touching the horizontal photovoltaic surface of trap 2; L, landing on the photovoltaic trap surface; H, hitting the tabanid trying to touch or land on the photovoltaic trap surface by a rotating wire. The solar elevation angle was calculated on the basis of the website <http://ephemeris.com> with the use of the geographical coordinates of the site of experiment 3 and the points of time.

Date (2010)	Time (UTC + 2 h)	Solar elevation (min–max) (°)	Tabanid reactions	Q_{capture} (%)
13 July	10:00–17:30	29.21–63.92	11 T + 6 L + 143 H	89.4
14 July	10:00–17:30	29.13–63.77	8 T + 7 L + 150 H	90.9
15 July	10:00–17:30	29.04–63.61	9 T + 4 L + 148 H	91.9
16 July	10:00–17:30	28.94–63.45	7 T + 3 L + 164 H	94.3
17 July	10:00–17:30	28.84–63.28	13 T + 3 L + 155 H	90.6
Sum			48 T + 23 L + 760 H	91.5 (average)

In experiment 4 we tested how a tilted supplementary photovoltaics can enhance the time period during which trap 2 can capture tabanid flies efficiently. Table 4 contains the number of tabanid reactions and the tabanid-capturing efficiency Q_{capture} of trap 2 in experiment 4, when the wire was rotating continuously with the use of the oblique (45° from the horizontal) supplementary photovoltaics. We found that in full sunshine trap 2 with the supplementary photovoltaics functioned excellently: from 9:00 to 19:00 h (UTC + 2 h) – during which the minima and

maxima of the solar elevation angle varied as given in Table 4 – the wire was rotating continuously with large enough angular velocities to hit and perish almost all tabanids trying to touch or land on the horizontal photovoltaic trap surface. Q_{capture} of trap 2 with the supplementary photovoltaics ranged from 93.2% to 94.7% with an average of 94.1%.

From experiment 4 we concluded that if the solar elevation angle was not lower than about 10° (Table 4), trap 2 with the supplementary photovoltaics functioned

Table 4

Number of reactions of tabanid flies N_T^{rotating} , N_L^{rotating} , N_H^{rotating} and the tabanid-capturing efficiency $Q_{\text{capture}} = N_H^{\text{rotating}} / (N_H^{\text{rotating}} + N_T^{\text{rotating}} + N_L^{\text{rotating}})$ of trap 2 in experiment 4, when the wire was rotating continuously with the use of a tilted supplementary photovoltaics. T, touching the horizontal photovoltaic surface of trap 2; L, landing on the horizontal photovoltaic trap surface; H, hitting the tabanid trying to touch or land on the horizontal photovoltaic trap surface by a rotating wire. The solar elevation angle was calculated on the basis of the website <http://ephemeris.com> with the use of the geographical coordinates of the site of experiment 4 and the points of time.

Date (2010)	Time (UTC + 2 h)	Solar elevation (min–max) (°)	Tabanid reactions	Q_{capture} (%)
2 August	09:00–19:00	11.49–59.84	10 T + 5 L + 205 H	93.2
3 August	09:00–19:00	11.29–59.58	8 T + 4 L + 198 H	94.3
4 August	09:00–19:00	11.08–59.32	9 T + 3 L + 188 H	94.0
5 August	09:00–19:00	10.87–59.05	7 T + 6 L + 219 H	94.4
6 August	09:00–19:00	10.65–58.78	11 T + 1 L + 215 H	94.7
Sum			45 T + 19 L + 1025 H	94.1 (average)

excellently in full sunshine and it could perish tabanids attracted to its horizontal photovoltaics with an efficiency of about 94%. If the additional photovoltaics was not turned always toward the sun, the tabanid-capturing efficiency of trap 2 inevitably decreased when the fixed supplementary photovoltaics did not point toward the sun. Since the abundance of tabanids is usually highest in early afternoon, it is worth orienting the fixed supplementary photovoltaics towards South or South-West on the northern hemisphere.

4. Discussion

In our field experiments we showed that positively polarotactic, water-seeking male and female horseflies can be attracted to a highly and horizontally polarizing horizontal photovoltaic surface, and the attracted tabanids can be perished by the mechanical hit of a wire rotated with an electromotor supplied by the direct electric current produced by the photovoltaics. These are the bases of the new concept of tabanid traps, in which the photovoltaics is bifunctional: (i) its horizontally polarized reflected light signal attracts water-seeking, polarotactic tabanids and (ii) it produces the electricity necessary to rotate the wire.

This new trap can capture (hit and perish) tabanids with an efficiency of about 92% in full sunshine if the solar elevation angle is not lower than about 29° (Table 3). Using an obliquely oriented supplementary photovoltaics with the same area as that of the horizontal photovoltaic trap surface, the capturing efficiency can be increased to about 94% and the capturing period can be extended by a few hours, if the solar elevation angle is not lower than about 10° (Table 4).

If the supplementary photovoltaics does not follow the solar azimuth direction, its optimal orientation is South or South-West, since in afternoon, partly due to the higher air temperature, more tabanids are flying than in forenoon. If the azimuthal orientation of the additional photovoltaics is constant, then, depending on its orientation, the period when the trap can efficiently capture tabanids is reduced by a few hours in comparison to the situation when the supplementary photovoltaics follows the solar azimuth direction. Without a supplementary solar panel the trap possessing only a horizontal photovoltaics is able to perish tabanids with a few hours shorter period than the same trap with a tilted supplementary photovoltaics.

If the sun is occluded by clouds, or the photovoltaic surfaces of the trap get into the shade of trees or buildings, the photovoltaics produces so small electricity that the wire cannot rotate with a large enough angular velocity to hit and perish tabanids touching or landing on the horizontal photovoltaic trap surface. Thus, one of the prerequisites of an efficient functioning of this new tabanid trap is that its photovoltaic surfaces must be exposed to full sunshine. However, the reduction of the capturing efficiency due to the occlusion of the sun by clouds is not a serious problem, because tabanids usually do not fly when the sun is hidden by clouds (Horváth et al., 2008, 2010a,b; Kriska et al., 2009; Egri et al., 2012 + personal observations).

The new tabanid trap, of course, must be water-proof, since it also has to function after rains. The realization of

water-proofness is not an easy task of engineering, but a solvable problem.

We experienced that the rotating wire can coil to the rotation axis of the electromotor, if a larger insect, leaf or branch falls onto the horizontal photovoltaic trap surface. In this case the shape of the kinked wire becomes spiral like, thus losing its practicability. Then the kinked wire has to be replaced with an intact, slightly upward-bending new one. Therefore, it is important that the aluminium head of the rotating axis of the electromotor must be constructed in such a way that in it the wire can be manually and easily exchanged. Furthermore, if possible, the trap should not be placed beneath trees.

A disadvantage of the new photovoltaic tabanid trap is that it may also attract and perish other, non-tabanid polarotactic insects, such as water beetles, aquatic bugs and dragonflies, for example. However, on the one hand, aquatic insects are usually not protected animals due to their abundance. On the other hand, the horizontal photovoltaic trap surface is only 60 cm × 60 cm, being too small to attract many aquatic insects. Aquatic insects require a species-specific minimal surface area of the water bodies into which their eggs are laid and where their larvae can develop successfully (Bailey and Ridsdill-Smith, 1991; Williams and Feltmate, 1992).

A further disadvantage to the photovoltaic trap is its complexity relative to the conventional tabanid traps. Due to the electronics and the rotating wire, the electronic and moving components can go wrong. The prize of this trap is also larger than that of normal traps because of the necessary photovoltaics and water-proof electronics.

When the new photovoltaic tabanid trap is used in the field, it could hurt animals and humans with its rotating wire. To avoid such injuries, the trap should be settled on the ground in such places, where animals or humans cannot approach it. Otherwise, the trap has to be enclosed by an appropriate fence (e.g. a wire grid) to hinder animals and humans to touch the rotating wire.

According to our experience, it is advantageous, if in its sedent stage the wire of the trap curves slightly upward (see Fig. 4A and B). During its rotation the originally slightly upward bending wire becomes straight due to the centrifugal force. If the wire were straight in its stillness, it would bend downward because of gravitation and would touch the horizontal photovoltaic trap surface. In this case, immediately after the switch on of the electromotor, the peripheral section of the wire would lag behind the central section due to the friction force of the underlying trap surface. Then the wire getting into a spin can easily coil to the motor's rotation axis. Due to the same effect, the flexible wire cannot be replaced by a string having a tiny weight at its ends (then the lag of the weights due to friction would cause the coil of the string onto the rotation axis).

It is worth using light-emitting diodes (LEDs) on the outer walls of trap 2. The function of these LEDs is that in the evening and at night their light signal can mark the position of the trap and call the attention of animals or humans passing by in order to avoid the trap. The LEDs can be supplied with the electricity produced by the photovoltaics during sunshine and stored in an in-built battery. In this case an additional electronic module is required to charge this

battery with the direct current produced by the photovoltaics and not used by the electromotor rotating the wire.

In comparison to sticky traps using insect-monitoring glues or liquids, an advantage of the new photovoltaic trap presented in this work is that the carcasses of the captured tabanids do not remain on the tabanid-attracting horizontal trap surface, since the hit tabanids are thrown away by the rotating wire to the neighbouring ground areas. Thus, this new trap does not lure and perish insectivorous birds with the tabanid carcasses, not like certain kinds of sticky insect traps. Although the new tabanid trap has an active part, the wire rotated by an electromotor, its actuation does not require an additional power supply (e.g. a battery), because the necessary electricity is produced by the photovoltaics of the trap.

The attractivity of the photovoltaic trap to tabanids could be enhanced with the use of certain chemicals (e.g. ammonia, carbon-dioxide, phenols) preferred by tabanid flies (Hribar et al., 1992; Mihok and Lange, in press). The field test of such an odour-baited photovoltaic trap could be the task of future research.

Finally, we would like to emphasize that in this work our major goal was to present a novel concept of tabanid traps based on light polarization and electricity produced by photovoltaics. The attraction and capture principles of this new trap are fundamentally different from those of the existing tabanid traps (Malaise, 1937; Gressitt and Gressitt, 1962; Catts, 1970; Chvala et al., 1972; von Kniepert, 1979; Wall and Doane, 1980; Hribar et al., 1992; Mihok, 2002; van Hennekeler et al., 2008; Mihok and Lange, in press). Studying the possible position of the photovoltaic trap in the marketplace and the comparison of this new trap with other traps could be the tasks of future investigations. Although beyond its advantages the new trap has also a few disadvantages, we showed here that its novel concept – based on highly and horizontally polarizing photovoltaics and the positive polarotaxis of tabanids – functions well in reality. Thus, in the future it is worth improving the technique and design of this photovoltaic tabanid trap, the concept of which is patented in Hungary (patent number U-11-00276: insect-perishing construction, especially tabanid trap using photovoltaics and a wire rotated with the electricity produced by the photovoltaics).

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