Near-Infrared (NIR)-Reflectance in Insects – Phenetic Studies of 181 Species

Infrarot (NIR)-Reflexion bei Insekten – phänetische Untersuchungen an 181 Arten

MICHAEL MIELEWCZIK, FRANK LIEBISCH, ACHIM WALTER & HARTMUT GREVEN

Summary: We tested a camera system which allows to roughly estimate the amount of reflectance properties in the near infrared (NIR; ca. 700-1000 nm). The effectiveness of the system was studied by taking photos of 165 insect species including some subspecies from museum collections (105 Coleoptera, 11 Hemiptera (Pentatomidae), 12 Hymenoptera, 10 Lepidoptera, 9 Mantodea, 4 Odonata, 13 Orthoptera, 1 Phasmatodea) and 16 living insect species (1 Lepidoptera, 3 Mantodea, 4 Orthoptera, 8 Phasmatodea), from which four are exemplarily pictured herein. The system is based on a modified standard consumer DSLR camera (Canon Rebel XSi), which was altered for two-channel colour infrared photography. The camera is especially sensitive in the spectral range of 700-800 nm, which is well-suited to visualize small scale spectral differences in the steep of increase in reflectance in this range, as it could be seen in some species. Several of the investigated species show at least a partial infrared reflectance. NIR-reflectance is especially pronounced in specimens of an overall white, red, orange and yellow colouration, but was also found in numerous green insects (e.g. the leaf katydids *Ancylecha fenestrata* and *Stipnochlora couloniana* and the walking leaf *Phyllium celebicum*). In contrast, other green wings, as for example the metallic green wings of the butterfly *Troides priamus* or the metallic green elytra of several jewel beetles such as *Chrysaspis aurovittata*, do not reflect NIR-radiation.

Keywords: infrared photography, NDVI, infrared reflectance, cuticle, insect, phenotyping

Zusammenfassung: Wir stellen ein Kamerasystem vor, mit dem man in erster Annäherung die Reflexionseigenschaften von Insekten im Nah-Infrarotbereich (NIR; etwa 700-1000 nm) bestimmen kann und haben dies anhand von entsprechenden Aufnahmen von 165 Insektenarten aus Sammlungen (105 Coleoptera, 11 Hemiptera (Pentatomidae), 12 Hymenoptera, 10 Lepidoptera, 9 Mantodea, 4 Odonata, 13 Orthoptera, 1 Phasmatodea) und 16 lebenden Insektenarten (1 Lepidoptera, 3 Mantodea, 4 Orthoptera, 8 Phasmatodea) geprüft, von denen wir vier Arten hier exemplarisch abbilden. Das System beruht auf einer modifizierten Standard-Digitalen Spiegelreflexkamera (Canon Rebel XSi), welche für den Einsatz als Zweikanal-Farbinfrarotkamera umgebaut wurde. Die Kamera ist besonders empfindlich im spektralen Bereich zwischen 700 und 800 nm, da in diesem Bereich oft kleinere Unterschiede der Steigung im Anstieg in der Reflexion bei verschiedenen Arten unterschieden werden können. Von den untersuchten Insektenarten zeigen einige zumindest partiell eine NIR-Reflexion. Diese ist besonders deutlich bei weißen, roten, orangefarbenen, gelben und besonders ausgeprägt bei einer Reihe von grünen Insektenarten (z. B. bei den Blattheuschrecken Ancylecha fenestrata und Stipnochlora couliana sowie dem Wandelnden Blatt Phyllium celebicum). Im Gegensatz dazu zeigen die Flügel anderer grüner Insektenarten, wie die metallisch grünen Elytren einer Reihe von Prachtkäfern, z. B. Chrysaspis aurovittata, oder die leuchtend grünen Flügel des Schwalbenschwanzes Troides priamus keine NIR-Reflexion.

Schlüsselwörter: Infrarot-Fotografie, NDVI, Infrarotreflexion, Kutikula, NIR, Insekten, Phänotypisierung

1. Introduction

Insects are variously coloured and the colouration has variegated functions such as advertisement, warning, crypsis etc. (for review see Cott 1940; Fox 1979; Chapman 1998; LUNAU 2011). Typically, the colouration is produced by physical means (e.g. diffraction, interference and scattering by nanostructures) and/or by pigments that absorb or emit light, and both, nanostructures and pigments, have been thoroughly studied in insects (for review see CROMARTIE 1959; Fox 1976; VIGNERON & SIMONIS 2010). However, investigations concerning insects primarily cover colouration patterns and their spectral reflectance characteristics in the range from 400 to 700 nm, which is visible for humans and many other vertebrates (visible spectrum of light = VIS), and the short-wave spectrum (ultraviolet/UV, 300-400 nm). Perceiving these patterns enable insects to recognize mating partners, hosts, food etc. (see MENZEL 1979; KELBER et al. 2003). Studies of infrared reflectance of the insect integument, i.e. between 700 and 1400 nm (near infrared = NIR), are rare, even though initial studies of insects were already performed by some of the early pioneers in infrared photography (TRISTAN & MICHAUD 1916). COTT (1940) was one of the first authors, who paid attention to infrared photography to study different green animals that may greatly differ in their absorption of infrared light. He presented infrared photographs showing a tettigoniid grasshopper that clearly contrasted against the background of green leaves, whereas the green caterpillar of Smerinthus ocellatus merges with the surrounding vegetation (see COTT 1940, plates 3 & 5).

In the present note we revive these studies by screening NIR-reflectance of a larger number of dead and living insects. In detail we 1) report on some basic principles of the red-edge based NDVI-photography we used for this phenetic screening, 2) present the results obtained from altogether 181 species including some subspecies (some of them are shown in NDVIphotographs), and 3) shortly touch the nature of infrared reflectance and its possible adaptive value. Generally, our study indicates that NIR-reflectance of insect integuments seems to be more widespread than the existing literature suggests.

2. Material and methods

2.1. Animals

We examined 165 species from the collection of the Aquazoo/Löbbecke-Museum Düsseldorf and the Entomological Collection of the ETH Zürich, i. e. 105 Coleoptera, 11 Hemiptera (Pentatomidae), 12 Hymenoptera, 10 Lepidoptera, 9 Mantodea, 4 Odonata, 13 Orthoptera, 1 Phasmatodea (Tab. 1; see appendix) and 16 living insect species, i.e. 1 caterpillar (Lepidoptera), 3 Mantodea, 4 Orthoptera, 8 Phasmatodea) (Tab. 2; see appendix). We included a large number of green specimens, as it is known from vertebrates that even though specimens can show a comparable green colouration, reflectance in the NIR-might be completely different (SCHWALM et al. 1977; DODD 1981; KREMPELS 1989; EMERSON et al. 1990). From the museum specimens colour photos and infrared images were taken under the same conditions, the latter with a modified DSLR (digital single-lens reflex) camera (see 2.2.). Colour images were acquired with a Canon EOS 550D and 600D camera. Images of specimens from terraria were taken under the local lighting conditions. Green leaves were used as references to quantify the amount of infrared reflectance. All images were acquired in highest quality as JPEG or Canon Raw image files.

Generally we adopted the scientific names of the insects directly from the collections. In a few cases we changed the species epithethon or the genus name.

2.2. Digital infrared and red edge photography

For image capture a modified handheld 12.2 megapixel DSLR camera (Canon Rebel XSi, modified by LDP LLD, Carlsted, USA, www. maxmax.com) was used. Such cameras are successfully used in monitoring the cover of vegetation (e.g. BOKHORST et al. 2012) by calculating the normalized difference vegetation index (NDVI) as described below. The camera is therefore advertised as NDVI-camera, a term we also use in this study. Here we apply the same camera to differentiate NIR-reflecting and NIR-nonreflecting insects and their surrounding surfaces. The modified camera detects light in two wave length bands in the range of blue light (B, 370 to 480 nm) and in the range of the so called red edge (RE). The red edge lies between red and near infrared (NIR) and is characterized by a wave length ranging from 675 to 775 nm.

The 2-band model offers the possibility to differentiate between NIR-reflecting and NIR-non-reflecting surfaces already by viewing the images. The former appear strongly red, whereas the latter appear (dark) blue. Discrimination of NIR-reflecting and non-reflecting surfaces can be easily performed using the 2-band images without normalization (see below), as human vision itself can differentiate blue and red. For an initial test of the camera we used two green vertebrate species (Morelia viridis and a green Furcifer pardalis), which are known to differ in their infrared reflectivity markedly (Dodd 1981; Krempels 1989; Gehring & WITTE 2007) (Fig. 1). Two examples for colour rendering of different natural material provided by the modified two channel NDVI-camera are given in figure 2. Differences are quite clear; therefore we think that normalization procedures for the images are not necessary in many cases. However, for quantitative analyses and comparison of insect images taken under different light intensities, the calculation of the NDVI-might be beneficial.

NDVI = (RE-B)/(RE+B)

Using the equation, we tested the hypothesis that the flash integrated in the camera and a white balance (white card) are useful to standardize image quality and small scale differences under different light regimes (Fig. 3 A). We selected areas on images of typical background vegetation such as grass (examples can be seen in Fig. 2 A, B).

To evaluate the image quality and identify an optimal image procedure for image acquisition we therefore compared NDVI-results under sunny and shadowy conditions (Fig. 3 B). Based on those findings, which clearly show that good illumination conditions are preferable, we used the internal camera flash for all photos. Images of the insect collections were acquired with an additional illumination provided by a 500 W halogen lamp to provide sufficient light in the NIR-range of the spectrum. All figures were prepared using Adobe Photoshop CS5 and Corel Draw X4. Box plots in figure 3 were created and based on statistical analysis performed with R 2.15.1 (R-Development-Core-Team, 2008).

2.3. Abbreviations

B = blue light; NDVI-= normalized difference vegetation index; NIR-= near infrared (700-1400 nm); RE = red edge (~700-800 nm); VIS = visible spectrum (400-700 nm); CCD = charged coupled device; CMOS = complementary metal-oxide semiconductor; DSLR = digital single-lens reflex.

3. Results

3.1. Optimizing image acquisition

The NDVI-camera is not only highly efficient in analysing differences of vegetation reflectance, but also to differentiate high from low reflectance items (Fig. 3 A, B).



Fig. 1: The NDVI-camera clearly shows reflectance differences in the NIR. Contrary to the green tree python *Morelia viridis* (**A**), the green panther chameleon *Furcifer pardalis* (**B**) shows a high NIR-reflectance, which is comparable to that of green coloured leaves (**C**).

Abb. 1: Die NDVI-Kamera zeigt deutlich Reflexionsunterschiede im Infrarotbereich. Im Gegensatz zum grünen Baumpython *Morelia viridis* (**A**) zeigt das grüne Pantherchamäleon *Furciger pardalis* (**B**) eine starke Reflexion, ähnlich der Reflexion der grünen Blätter (**C**).



Fig. 2: Colour rendering of the infrared sensitive NDVI-camera. A Landscape with different materials. Vegetation appears pink to light red (high NIR-reflectance), stones and sand are violet to blue (low NIR-reflectance). B Depending on shadow, illumination, kind of leaves and light quality, vegetation may show small variations, but the high reflectance in the NIR is always obvious. However, other colours than green, e.g. the yellow fur of a tiger (*Panthera tigris*), reveal a similar NIR-reflectance as the vegetation.

Abb. 2: Farbrendering der infrarotsensitiven NDVI-Kamera. **A** Landschaft mit verschiedenen Materialien. Die Vegetation erscheint pink oder rot (hohe NIR-Reflexion), Steine und Sand sind violett bis blau (niedrige NIR-Reflexion). **B** In Abhängigkeit von Schatten, Lichtintensität, Blattbeschaffenheit und Lichtqualität kann die Farbdarstellung der Vegetation variieren, jedoch ist die starke Reflexion im NIR klar erkennbar. Auch andere sichtbare Farben als Grün können eine ähnlich starke Infrarotreflexion aufweisen, z.B. weist das orangerote Fell des Tigers (*Panthera tigris*) eine ähnliche NIR-Reflexion auf wie die Pflanzen im Schatten.

Using a white card and the integrated camera-flash clearly shows that under shadowy conditions NDVI-values of different background vegetation increase and variation decreases (Fig. 3 A). Further, it is shown that under strong light regimes the differences between samples are more pronounced (Fig. 3 B). Images of specimens were thus all acquired using automatic white balance and the internal compulsory flash of the camera.

Even though limited to a two colour model, the acquired images share a colouration scheme, which is highly comparable to those of film-based, classic 3-colourinfrared photography (for comparisons see GIBSON 1978).

3.2. NIR-reflectance in insects

Generally, our NIR-images reveal a remarkable variation not only concerning the occurrence of NIR-reflectance, but also concerning the reflectance patterns (for an overview see Tabs. 1, 2; Figs. 4-10). Only for description we herein use five categories to characterize reflectance: no, very weak, weak, medium, strong (see Fig. 4).

3.21. Coleoptera (museum specimens)

Black beetle species such as Carabus scabrosus typically show no NIR-reflectance. In contrast, most dark brownish to red brownish specimens show a weak to medium reflectance. Such beetles were found in nearly all groups of brownish coleopteran investigated, e.g. in the Buprestidae, Dynastidae, Elateridae and Scarabidae (see Tab. 1; Fig. 5). Beetles, which possess orange, yellow or red colouration or markings, typically possess a higher NIR-reflectance than darkbrown specimens. In some cases (e. g. in Eudicella smithi or Sternotomis bohndorfii) the orange legs or antennas showed a medium NIR-reflectance. The highest phenetic plasticity was found in green-coloured beetles. Most metallic green beetles, as for example Sternocera sternicornis, Sternotomis bohndorfii and Stephanorrhina guttata, do not show a marked NIR-reflectance, in contrast to their orange patterns. There was also a small number of green beetles (for example Smaragdesthes africana and Caelorrhina superba), in which a medium reflectance could be found. In C. superior five of the examined specimens did not show any NIR-reflectance, while two

Fig. 3: A NDVI-values of grass vegetation under shadowy (left) and sunny (right) conditions as affected by the corrective treatments (norm = without corrective treatment, wb = white card used for image capture, wb+flash = white card and internal flash used for image capture). The NDVI-values increase, when a white card and a white card plus internal flash of the camera are used under shadowy conditions. Under sunny conditions NDVI-values are highest and corrective measures have no effect. In the boxplots (n = 9 replicates) the horizontal line represents the median, the bottom and the top of the box show the 25th and 75th percentile, respectively, and whiskers represent either the maximum value or 1.5 times the interquartile range, which ever is the smaller. Points higher than 1.5 times are shown as single points (potential outlier). **B** Differences of various background vegetation samples under shadowy (top) and sunny (bottom) conditions (n = 3). A better light regime reduces the variance and allows a better discrimination of the different surfaces.

Abb. 3: A NDVI-Werte von Grasvegetation unter schattigen (links) und sonnigen (rechts) Umweltbedingungen in Abhängigkeit von Korrekturen während der Aufnahmen (norm = ohne Korrektur, wb = Weißabgleich mit weißer Karte während der Bildaufnahme, wb+flash = Weißabgleich mit gleichzeitig verwendetem Blitz). Durch den Einsatz der weißen Karte und der weißen Karte mit Blitz steigt der NDVI-Wert unter schattigen Bedingungen. Unter sonnigen Bedingungen sind die NDVI-Werte am größten und die zusätzlichen Korrekturmaßnahmen haben keinen Effekt. In den Boxplots (n = 9 Replikate) repräsentiert die horizontale Linie den Median und das untere und obere Ende der Box jeweils den 25- und 75-Perzentil. Die Whisker zeigen entweder den Maximalwert



oder den 1.5-Interquartilbereich. Einzelpunkte zeigen Werte außerhalb dieses Bereichs (potenzielle Ausreißer). **B** Unterschiede zwischen verschiedenen Vegetationsbeispielen bei schattigen (oben) und sonnigen (unten) Bedingungen (n = 3). Bessere Lichtverhältnisse reduzieren die Varianz und machen verschiedene Oberflächen besser voneinander unterscheidbar.



Fig. 4: Different Pentatomidae species in a showcase. Overview (A) and NIR (B-F) and conventional color photos (G-K) of selected species, which either do not reflect NIR (B) or reflect (C) very weak, (D) weak, (E) with medium intensity and (F) high. (B+G) *Trochycoccris rotundatus*, (C+H) *Dolycoris baccarum*, (D+I) *Chlorochroa juniperina*, (E+J) *Palomena viridissima* and (F+K) *Nezara viridula*. Abb. 4: Verschiedene Pentatomiden in einem Schaukasten. Übersicht (A) sowie NIR- (B-F) und Farbaufnahmen (G-K) einzelner Arten, die entweder (B) kein NIR reflektieren oder (C) sehr schwach, (D) schwach, (E) mittelstark und (F) stark reflektieren. (B+G) *Trochycoccris rotundatus*, (C+H) *Dolycoris baccarum*, (D+I) *Chlorochroa juniperina*, (E+J) *Palomena viridissima*, (F+K) *Nezara viridula*.

showed either a weak or medium to strong reflectance (Fig. 6). The latter specimens showed a slight reddish tint in their green colouration when viewed in the visible spectrum.

3.2.2. Hemiptera (Pentatomidae, museum specimens)

Black specimens, e.g. *Trochicocoris rotundatus*, did not show any NIR-reflectance in the black parts of their body (see Fig 4, Tab. 1). In contrast, in green and brown specimens of *Chlorochroa juniperina*, *Dolycoris baccarum*, *Palomena prasina* and *Palomena viridissima* various shades of NIR-reflectance were found (Fig. 4 A, C-E). *Nezara viridula* showed an exemplarily high NIR-reflectance.

3.2.3. Hymenoptera (museum specimens)

NIR-reflectance of the black body parts was low in all Hymenoptera species investigated (Tab. 1), whereas the yellow striped markings of different wasps showed a medium reflectance. The transparent wings appearing yellowish in the visible spectrum showed a higher reflectance.

3.2.4. Lepidoptera (museum and living specimens)

Dark patterns of caterpillars from museum specimens generally showed a reduced or no NIR-reflectance. The green caterpillars of *Endromis versicoloura* and *Saturnia pavonia* revealed a medium reflectance. A high NIR-reflectance was found in living green caterpillars of the Atlas moth *Attacus atlas* (Fig. 7). Cocoons of this species showed a weak to medium reflectance comparable to that of bark. Brown wing parts of adult butterflies such as *Prepona chromus* typically show a weak to medium reflectance. The light blue markings of this species and the Paris peacock *Papilio* *paris* showed a somewhat higher reflectance, compared to the rest of the wings. A higher reflectance was also found in yellow or orange markings of *Papilio euchenor* and *Teinopalpus imperialis*. The green iridescent areas on the wings of *T. imperialis* and *P. paris* showed a very weak NIR-reflectance, if any.

3.2.5. Odonata (museum specimen)

In contrast to the yellow spots on the abdomen of a female *Libellula depressa*, the dark body parts of Odonata species did not show any NIR-reflectance (see Tab. 1). Whitish transparent exuviae of various unclassified species generally showed a high reflectance (data not shown).

3.2.6. Mantodea, Orthoptera and Phasmatodea (museum and living specimens)

A green living specimen of *Mantis religiosa* showed an extremely high NIR-reflectance, comparable to that of green leaves (Tab. 2). The brownish wandering violin mantis Gongylus gongylodes showed only a weak to medium reflectance, similar to the twigs in its terrarium. Similar observations were made on several other green and brown species of Orthoptera and Phasmatodea (Tab. 2). Green leaf katydids such as Ancylecha fenestrata and Stilpnochlorchis couloniana showed a strong NIR-reflectance comparable to that of green leaves (Fig. 8). Yellow or green coloured body parts of Schistocerca gregaria showed a strong reflectance. This also applies to juvenile stages that, however, possess large black, non-reflecting markings. Very young nymphs are completely black and easy to discriminate from background vegetation in the NIR-photos. We also observed a slight sexual dimorphism in this species regarding NIR-reflectance (Fig. 9). A very high NIR-reflectance was also observed in green Phasmato-



Fig. 5: Specimens of different beetle species shown in conventional colour (**A,C,E**) and NIR-photos (**B,D,F**). The brown to red brown jewel beetle *Sternocera hildebrandti* (**A+B**) shows a medium NIR-reflectance, as the light brown elytra of the stag beetle *Dicranocephalus bowringi* (**E+F**). The green cetoniid *Ischiosopha lucivorax* (**C+D**) does not show any NIR-reflectance.

Abb. 5: Individuen von verschiedenen Käfern gezeigt in Farb- (**A**,**C**,**E**) und NIR- (**B**,**D**,**F**) Fotografie. Die braun bis rotbraunen Prachtkäfer *Sternocera hildebrandti* (**A**+**B**) zeigen eine mittlere NIR-Reflexion, wie die hellbraunen Flügeldecken des Hirschkäfers, *Dicranocephalus bowringi* (**E**+**F**). Die grünen Rosenkäfer *Ischiosopha lucivorax* (**C**+**D**) zeigen keine NIR-Reflexion.



Fig. 6: Specimens of the rose chafer *Caelorthina superba* (**A**) differ considerably concerning NIR-reflectance (**B**). Black beetles such as *Carabus scabrosus tauricus* (**C**) generally do not show NIR-reflectance (**D**).

Abb. 6: Individuen des Rosenkäfers *Caelorrhina superba* (**A**) unterscheiden sich hinsichtlich ihrer NIR-Reflexion beträchtlich (**B**). Schwarze Käfer wie *Carabus scabrosus tauricus* (**C**) zeigen generell keine NIR-Reflexion (**D**).

dea species such as *Heteropteryx dilatata, Diapherodes gigantea* and *Phyllium celebicum*. In contrast, brown Phasmatodea as *Extatosoma tiaratum* appeared darker and blueish in NIR-images similar to the colouration of twigs and dry brown leaves. Observations from living specimens generally agree with those of dead museum specimens. Yet, it should be noted that colours of green and yellow Mantodea and Orthoptera species in the collection tend to fade.

4. Discussion

Techniques of infrared photography are at hand now for more than 100 years, beginning with the discovery that vegetation or better green leaves possess an extremely high reflectance in the NIR-range of the spectrum and, thus, appear snow-white in monochrome infrared images (Wood 1910 a, b). This unusual photographic peculiarity is commonly known as the Wood effect,



Fig. 7: The bluish-green caterpillar of the Atlas moth $Atllacus atlas(\mathbf{A})$ exhibits a high NIR-reflectance (**C**), which markedly differs from that of the leaves because of its high blue light reflection. The seemingly higher NIR-reflectance of the leaves is caused by their low blue light reflectance. The brownish cocoon shows a much lower reflectance in both wave bands (**B**).

Abb. 7: Die blau-grüne Raupe der Atlasmotte *Attlacus atlas* (**A**) weist eine hohe NIR-Reflexion auf (**C**), die sich wegen ihrer starken Blaulichtreflexion stark von der der NIR-Reflexion der Blätter unterscheidet. Die scheinbare höhere NIR-Reflexion der Blätter ist durch ihre geringe Blaulichtreflexion bedingt. Die braune Puppe zeigt eine viel geringere Reflexion in beiden Wellenlängenbereichen (**B**).



Fig. 8: The Malaysian katydid *Ancylecha fenestrata* (**A**) shows a strong NIR-reflectance (**B**). **Abb. 8:** Die Malaysische Blattschrecke *Ancylecha fenestrata* (**A**) zeigt eine starke NIR-Reflexion (**B**).

a term still widely used by enthusiastic amateurs and professional infrared photographers. Since then infrared photography has been frequently used in different fields

a term still widely used by enthusiastic of science (e.g. CLARK 1947; GIBSON 1978; amateurs and professional infrared photo- VERHOEVEN 2008).

More recently film-based infrared photography has been substituted by digital



Fig. 9: The female of the desert locust *Schistocerca gregaria* appears slightly darker compared to the male that shows a NIR-reflectance similar to the grass vegetation; the nymphs (on the top) do not reflect any NIR.

Abb. 9: Das Weibchen der Wanderheuschrecke *Schistocerca gregaria* erscheint etwas dunkler als das Männchen, das eine sehr starke NIR-Reflexion zeigt; die Nymphen (oben) reflektieren kein NIR.



Fig. 10: The leaf insect *Phyllium celebicum* (\mathbf{A}) and its NIR-reflectance (\mathbf{B}) similarly strong as the surrounding vegetation.

Abb. 10: Das Wandelnde Blatt *Phyllium celebicum* (**A**) reflektiert im NIR (**B**) ähnlich stark wie die umgebende Vegetation.

cameras, with the consequence that colour infrared films are no longer available (VERHOEVEN 2008) and that commercial laboratories have ceased film processing.

In principle, however, all CCD (chargecoupled device) and CMOS (complementary metal-oxide-semiconductor) sensors of digital consumer cameras are also sensitive to near-infrared up to 1100 nm due to the intrinsic physical properties of silicon (Fredembach & Süsstrunk 2008, 2010). Yet, in front of the CCD sensor a more or less efficient "hot-mirror" is integrated into the camera sensor to block infrared light, which improves the overall image quality. Therefore, any consumer DSLR camera can be used to acquire NIR-images, if the exposure time is sufficiently long and if a filter is used to block the visible light (VERHOEVEN 2008). However, very long exposure times are often not practicable and may reduce image quality, but most digital consumer cameras can be modified into NIR-sensitive cameras by removing the internal hot-mirror (used in normal photography to block NIR-light) and using different red or infrared band-pass filters, similar to those used in classical infrared photography (see GIBSON 1978 for filters used in infrared photography and TETLEY & YOUNG 2007, 2009 for details on infrared camera modification). Commonly, those filters can be attached either to the front lens of the camera or they are mounted behind the lens on the sensor during camera modification. As filter usage is not standardized presently, digital colour infrared photography requires digital post-processing, e.g. manual colour adjustments.

The herein presented results show that the modified NDVI-camera used by us is an efficient and useful alternative to perform digital infrared photography for scientific purposes (for references on digital infrared photography see VERHOEVEN 2008). Advantages are a colour scheme based on two bands, which is not only easy to understand, but also matches partially the false colour rendering of previous colour infrared films (for reference see GIBSON 1978). Concerning applied NIR-photography, the NDVIcamera has several advantages: (1) It is not necessary to apply any additional filter in front of the lens to block the visible light, as the filter has been integrated back-lens

directly on the CCD sensor by the manufacturer. In consequence, both the view finder and the live view mode are fully functional. (2) There are also no limitations to autoexposure and sensor cleaning functions. (3) The narrow RE-bandwidth of the camera limited to the range of about 675 to 800 nm. Therefore any problems related to wavelength-dependent shifts in the camera focus typically occuring in NIRphotography are minimized and even the autofocus can be used. (4) There appear to be no limitations concerning the use of various lenses.

For general visualization of differences in NIR-reflectance it does not appear to be necessary to normalize the generated images (see equation p. 185), though it can be helpful whenever quantitative imaging is needed, e. g. in vegetation studies. Under shadowy condition (e. g. cloudy sky, tree canopy, indoor) image quality can be improved by using white cards and internal flashes. That in our study these NDVI-values did not reach NDVI-values obtained in full sun can be explained by the weak flash of the camera. Using a stronger external flash will probably increase these values. We showed that additional light during image capture improves image quality for analytical purposes.

Infrared photography for image-based phenotyping of animals has already been proposed by DODD (1981) and especially KREM-PELS (1989). Now digital infrared cameras enormously simplify this method, not only because it is easier to acquire many images in a short time, but also (even more important to our opinion) because time-consuming and costly film processing in a darkroom specifically equipped for infrared photography has become obsolete. In addition, recent digital consumer cameras have further advantages very useful for image-based phenotyping, i. e. additional meta-information can be automatically integrated into the image during image acquisition such as used lens, exposure time, flash mode etc., which can be accessed

later on any computer (MIELEWCZIK 2002, 2003 a, 2003 b). Also various epithetha can be attached to the images using additional meta-data fields provided by the IPTC image file extensions (see for example MIELEWCZIK 2007 a), which is helpful in managing huge databases with several thousand images. We believe it is best to acquire images in RAW and JPEG mode simultaneously. RAW image files generally provide the highest quality and degree of freedom for postprocessing purposes (see for example MIELEWCZIK 2007 b), while JPEG files are much easier to handle in day-to day-use due to their smaller size.

4.1. Infrared reflectance of insects

The most striking result of our study is the fact that many green insects show a very high NIR-reflectance, which closely resembles that of leaves. This was especially found in living specimens of walking leaves (Phasmatodea) and green Orthoptera such as Phyllium celebicum and Stilpnochlora couloniana. All species are known for camouflage and phytomimesis (for summary see LUNAU 2011). Spectral similarities between green insects, such as caterpillars, grasshoppers, mantis and walking leaves, and true leaves have been known for a long time (BECQUEREL & BRONGNIART 1894; PRZIBAM 1913). However, to our knowledge it has never been reported for any mantid or orthopteran species that this property extends into the NIR-range of the spectrum. Spectra of green insect species showing a high NIR-reflectance are known from a caterpillar (Rhodenia fugax: SAITO 2001) and in the metallic green beetles Calloodes grayanus (PARKER et al. 1998) and Charidotella egregia (VIGNERON et al. 2007).

4.1.1. Museum specimens

We found different intensities of NIRreflectance in a large number of dead specimens from the museum collections

that were dried and stored in drawers. This shows that these specimens retained this property at least in part. We assume that NIR-reflectance observed in these specimens is largely attributed to the organization and pigmentation of the cuticle; the underlying epidermis should be destroyed. The general "lamellate" structure for example of the elytron cuticle - hardly or not to be seen in the exocuticle - is conserved (e.g. VAN DE KAMP & GREVEN 2010). The same applies for structural colours of the cuticle, e.g. the multilayered reflectors in the cuticle of beetles (SEAGO et al. 2009), which can be identified even in fossils (PARKER & MCKEN-ZIE 2003; TANAKA et al. 2010; MCNAMARA et al. 2012). Also preserved are dark and brown patterns caused generally by tanning (elytra are often heavily sclerotized), but also by melanization, which was seen in many of the species examined.

However, some pigments appear to fade in course of the time, e.g. in the green and otherwise coloured species of Mantodea, Phasmatodea, Orthoptera and also in light coloured caterpillars. Their green and yellow patterns are caused by the simultaneous presence of selectively blue (carotenes) and red absorbing pigments, such as chromoproteins containing non-covalently bound biliverdin IXa as prosthetic group (PRZIBRAM & LEDERER 1933; KAWOOYA et al. 1985; OKAY 1945; PASSAMA-VUILLAUME & BARBIER 1966; RÜDIGER 1970; HOLDEN et al. 1987; WIL-LIG 1969). Therefore, we assume that here photo-oxidation and chemical degradation are responsible for bleaching, but, nevertheless, some NIR-reflectance is retained. We think that also some further parameters may affect NIR-reflectance such as thinness

may affect NIR-reflectance such as thinness of the cuticle and their dehydration. An opposite effect (i.e. higher reflectance) is known from stacking of leaves due to the reduced transmission (ALLEN & RICHARDSON 1968, see also GATES 1980). Further, drying of the cuticle may lead to another effect, also known from studies of leaves: Scattering coefficients in diffuse reflectance over the VIS and NIR-range of the spectrum generally increase in dehydrated tissues (ALLEN & RICHARDSON 1968; see GATES 1980). Dehydrated leaves show an increase in reflectance over the whole range of the spectrum from 400-2500 nm (CARTER 1991; RASCHER et al. 2007), although only the increased reflectance in the range of 1000 to 2500 nm is thought to be directly related to absorption of water (JACQUEMOUD et al. 1996; RASCHER et al. 2010). Nevertheless, the acquired NDVI-infrared images of the insects examined herein show areas and patterns of dark and brown colourations that are retained in the museum specimens and play a major role in the overall spectral and spatial absorption in the RE- and NIR-range of the spectrum.

Further, our study indicates that insect species with a considerably high NIRreflectance are found throughout the world and in different taxa. We think that this phenomenon might be more common in species living on leaves. Here, NIR-reflectance matches to the green background. Similarly, NIR-reflectance of dark or brown insects may match to their local substrate. Generally, however, the adaptive value of NIR-reflectance of insects and animals is largely unknown and only a few suggestions are given herein: KREMPELS (1989), who studied infrared reflectance of several frogs and squamates assumed an adaptive camouflage of predators and suggested that IR-reflectance in coral snakes contributes to their aposematic colouration. Interestingly, we found NIR-reflectance in the green predatory Mantis religiosa, which in turn may baffle its prey. Brownish or red colouration is accompanied by a weak to medium NIR- reflectance (Buprestidae: WAGNER 1971; and many other dark insects including several phasmids). This fits very well into the general cryptic protective strategies of many stick insects (Phasmatodae) (for review see BEDFORD 1978).

If these suggestions are right, putative predators or prey must be able to see in the NIR-and RE range of the spectrum. Spectral tuning of NIR-reflectance and the steep increase of reflectance in the RE might be beneficial to baffle predators that show a shift toward longer wavelengths in their spectral sensitivity. Up to date true sensitivity in the NIR, first suggested by early pioneers in infrared photography (TRISTAN & MICHAUD 1916), has been reported in a limited number of various invertebrate and vertebrate taxa, e.g. Crustacea (Mysis relicta: LINDSTRÖM & MEYER-ROCHOW 1987), Coleoptera (Hypera postica: Meyer 1976), Teleostei (Rutilus rutilus: LOEW & LYTHGOE 1985; Oreochromis mossambicus: Shcherbakov et al. 2012), Dipnoi (Neoceradotus fosteri: HART 2008), Squamata (Anolis carolinensis: Kawamura & Yokoyama 1998: Provencio et al. 1992), Mammalia (*Mustelus furo*: Newbold 2007, NEWBOLD & KING 2009). Infrared vision in birds (VANDERPLANCK 1934, WOJ-TUSIAK 1949) and turtles (WOJTUSIAK 1947) has been doubted (for discussions see for example MATTHEWS & MATTHEWS 1939, IN DEN BOSCH 1987).

It is also possible that reflectance in the far-red and near-infrared has an adaptive value with respect to interspecific visual interactions, as it has been suggested for example in fish and some squamates (PAR-TRIDGE et al. 1989; PROVENCIO et al. 1992). NIR-reflectance may also affect thermoregulation as heatload may be increased (for discussion see IN DEN BOSCH 1987). Furthermore, it had been suggested, that IR-reflectance might be only an inevitable by-product of the colour pattern in the visible part of the spectrum (IN DEN BOSCH 1987). For all suggestions convincing experimental evidence is missing.

To our knowledge the structural basis of IRreflectance is not yet satisfactorily clarified. In Lepidoptera pterin is suggested to contribute to the overall reflectance of the longer wavelengths within the visible spectrum (RUTOWSKI et al. 2005) and therefore may also cover the NIR-range. We believe that the very high NIR-reflectance demonstrated in various insects or their larvae is based on the structural properties of their integument, i.e. the cuticle and epidermis. These properties may lead to a broadband high and diffuse reflectance, spanning the VIS and NIR-spectrum. The NIRreflectance is furthermore characterized by absorption of brownish and dark pigments. Additional blue and red absorbing pigments such as erythropterin and carotenoids (blue absorbing) and biliverdin (red absorbing) occurring in both, the cuticle and the epidermis (LENAU & BARFOED 2008), may lead to the green appearance of the specimens. In addition, multiple layers with an alternating pattern of low and high refractive indices, as typical for the arthropod cuticle in general, can define not only visible colours (LAND 1966; LENAU & BARFOED 2008), but may also define NIR-reflectance.

Especially the various taxa of green metalliccoloured beetles such as Stephanorrhina guttata and some butterflies such as Teinopalpus imperialis show a wide range of variation in the intensity of NIR-reflectance, which may be related to the different modes of colour production (e.g. scattering, diffraction or interference effects) (for references see Fox & VEVERS 1960; CHAPMAN 1998; MICHIELSEN & STAVENGA 2008; LENAU & BARFOED 2008). More difficult to explain are interspecific differences as demonstrated in Caelorrhina superba. Here polarizing effects in the nanostructure may affect NIR-reflectance. Our study shows that high levels of NIR-reflectance are much more widespread among insects than to be expected from literature. Especially in green tropical Phasmatodea

and Orthoptera NIR-reflectance appears to be prevailing.

Acknowledgements

We thank Dr. SILKE STOLL (Aquazoo/Löbbecke-Museum der Stadt Düsseldorf) and Dr. ANDREAS MÜLLER and FRANZISKA SCHMID (Institute of Agricultural Sciences, Applied Entomology Group, ETH Zürich), who made available to us the insect specimens from the collection of the Museum, and SUSANNE TITTMANN (Forschungszentrum Geisenheim) for support in photography on excursions.

Literature

- ALLEN, W.A., & RICHARDSON, A.J. (1968): Interaction of light with a plant canopy. Journal of the Optical Society of America 58: 1023-1028.
- BECQUEREL, H., & BRONGNIART, C. (1894): La matière verte chez les Phyllies. Comptes rendus hebdomadaires des séances de l'Académie des sciences 118: 1299-1303.
- BEDFORD, G.O. (1978): Biology and ecology of the phasmatodea. Annual Review of Entomology 23: 125-49.
- BOKHORST, S., TØMMERVIK, H., CALLAGHAN, T.V., PHOENIX G.K., & BJERKE, J.W. (2012): Vegetation recovery following extreme winter warming events in the sub-Arctic estimated using NDVI-from remote sensing and handheld passive proximal sensors. Environmental and Experimental Botany 81: 18-25.
- CARTER, G.A. (1991): Primary and secondary effects of water content on the spectral reflectance of leaves. American Journal of Botany 78: 916-924.
- CHAPMAN, R.F. (1998): The insects. Structure and function. 3rd edition. University Press; Cambridge.
- CLARK, W. (1947): Photography by infrared Its principles and application. 2nd edition. John Wiley & Sons; London, New York.
- COTT, H.B. (1949): Adaptive colouration in animals. Methuen & Co Ltd.; London.
- CROMARTIE, R.I.T. (1959): Insect pigments. Annual Review of Entomology 4: 59-76.
- DODD, C.K. JR. (1981): Infrared reflectance in chameleons (Chamaeleonidae) from Kenya. Biotropica 13: 161-164.
- EMERSON, S.B., COOPER, T.A., & EHLERINGER, J.R. (1990): Convergence in reflectance spectra among treefrogs. Functional Ecology 4: 47-51
- Fox, H. M., & VEVERS, G. (1960): The nature of animal colours. Sidgwick and Jackson, London.

- Fox, D.L. (1976): Animal biochromes and structural colours – physical, chemical, distributional & physiological features of bodies in the animal world. 2nd edition. University of California Press; Berkeley.
- Fox, D.L. (1979): Biochromy Natural colouration of living things. University of California Press; Berkeley.
- FREDEMBACH, C., & SÜSSTRUNK, S. (2008): Colouring the near infrared. Pp. 176-182 in: Proceedings of IS & T/SID 16th Colour Imaging Conference; Portland.
- FREDEMBACH, C., & SÜSSTRUNK, S. (2010): Automatic and accurate shadow detection from (potentially) a single image using near-infrared information. IEEE Transactions on Pattern Analysis and Machine Intelligence 165527.
- GATES, D. (1980): Biophysical ecology. Springer; New York, Heidelberg, Berlin.
- GEHRING, P.-S., & WITTE, K. (2007): Ultraviolet reflectance in Malagasy chameleons of the genus *Furcifer* (Squamata: Chamaeonidae). Salamandra 43: 43-48.
- GIBSON, H.L. (1978): Photography by infrared: Its principle and applications. 3rd edition. John Wiley & Sons; London, New York.
- HADLEY, N.F., SAVILL, A., & SCHULTZ, T.D. (1992): Colouration and its thermal consequences in the New Zealand tiger beetle *Neocicindela perhispida*. Journal of Thermal Biology 17: 55-61.
- HART, N.S., BAILES, H.J., VOROBYEV, M., MAR-SHALL, N.J., & COLLIN, S.P. (2008): Visual ecology of the Australian lungfish (*Neoceratodus forsteri*). BMC Ecology 8: 1-14.
- HOLDEN, H.M., RYPNIEWSKI, W.R., LAW, H.L., & RAYMENT, I. (1987): The molecular structure of insecticyanin from the tobacco hornworm *Manduca sexta* L. at 2.6 Å resolution. EMBO Journal 6: 1565-1570.
- JACQUEMOUD, S., USTIN, S.L., VERBEDOUT, J., SCHMUCK, G., ANDREOLI, G., & HOSGOOD, B. (1996) Estimating leaf biochemistry using the PROSPECT leaf optical properties model. Remote Sensing of Environment 56: 194-202.
- IN DEN BOSCH, H.A.J. (1987): Über Missverständnisse bei der Deutung von Infrarotaufnahmen am Beispiel von *Chameleo jacksonii*. Herpetofauna 51:19-28.
- KAWAMURA, S., & YOKOYAMA, S. (1998): Functional characterization of visual and nonvisual pigments of American chameleon (*Anolis* carolinensis). Vision Research 38: 37-44.

- KAWAOOYA, J.K., KEIM, P.S., LAW, J.H., RILEY, C.T., RYAN, R.O., & SHAPIRO, J.P. (1985): Why are green caterpillars green? ACS Symposium Series – American Chemical Society 276: 511-521.
- KELBER, A., VOROBYEV, M., & OSORIO, D. (2003): Animal colour vision: behavioural tests and physiological concepts. Biological Reviews of the Cambridge Philosophical Society 78: 81-118
- KREMPELS, D.M. (1989): "Visible light" and nearinfrared reflectance of amphibians and reptiles and the visual system of avian predators (Accipitridae: *Buteo* spp). Dissertation Thesis: University of Miami; Miami.
- KUSUDA, J., & MUKAI, J.-I. (1971): A biliprotein from the digestive juice of *Bombyx mori* L. – Its purification and partial structural study of the chromophore. Comparative Biochemistry and Physiology Part B 39: 317-323.
- LENAU, T., & BARFOED, M. (2008): Colours and metallic sheen in beetle shells – A biometric search for material structuring principle causing light interference. Advanced Engineering Materials 10: 299-314.
- LOEW, E.R. & LYTHGOE, J.N. (1985): The ecology of colour vision. Endeavour 9 (4): 170-174.
- LOWREY, S., DE SILVA, L., HODGKINSON, I., & LEADER, J. (2007): Observation and modeling of polarized light from scarab beetles. Journal of the Optic Society of America A 24: 2418-2425.
- LUNAU, K. (2011): Warnen, Tarnen, Täuschen. Mimikry und Nachahmung bei Pflanze, Tier und Mensch. Wissenschaftliche Buchgesellschaft; Darmstadt.
- MATTHEWS, L.H., & MATTHEWS, B.H.C. (1939): Owls and infrared-radiation. Nature 143: 983.
- MCNAMARA, M.E., BRIGGS, D.E.G., ORR., P.J., NOH, H., & CAO, H. (2012): The original colours of fossil beetles. Proceedings of the Royal Society B 279: 1114-1121.
- MENZEL, R. (1979): Spectral sensitivity and colour vision in invertebrates. Pp. 503-580 in: AUTRUM, H. (ed.): Handbook of Sensory Physiology. Vol. VII/6A. Springer; Berlin, Heidelberg, New York.
- MEYER, J.R. (1976): Positive phototaxis of adult alfalfa weevils to visible and near-infrared radiation. Annals of the Entomological Society of America. 69 : 21-25.
- LINDSTRÖM, M., & MEYER-ROCHOW, V.B. (1987): Near infra-red sensitivity of the eye of the

crustacean *Mysis relicta*? Biochemical and Biophysical Research Communications 147: 747-752.

- MICHIELSEN, K., & STAVENGA, D.G. (2008): Gyroid cuticular structures in butterfly wing scales: biological photonic crystals. Journal of the Royal Society Interface 5: 85-94.
- MIELEWCZIK, M. (2002): Versteckte Informationen. PC Praxis Foto 2/2002: 113-114.
- MIELEWCZIK, M. (2003 a): Eldorado für Hobby-Fotografen – Zusatzinformationen zu Digitalfotos. Linux User 10/2003: 52
- MIELEWCZIK (2003 b): Extended information on digital photos – the perfect picture. Linux Magazine 11/2003: 34-35.
- MIELEWCZIK, M. (2007 a): Exif-Daten Zusatz-Infos nutzen. Chip Linux 1/2007: 54-55.
- MIELEWCZIK, M. (2007 b): Raw-Bilder unter Linux. Chip Linux 1/2007: 49-51.
- OKAY, S. (1945): Pigmentation of Orthoptera. Nature 155: 635.
- NEWBOLD, H.G. (2007): Infra-red vision in ferrets (*Mustelo furo*). Master Thesis, University of Waikato; Waikato, New Zealand.
- NEWBOLD, H.G., & KING, C.M. (2009): Can a predator see 'invisible' light? Infrared vision in ferrets (*Mustela furo*). Wildlife Research 36: 309-318.
- PARKER, A.R., MCKENZIE, D.R, & LARGE, M.C.J. (1998): Multilayer reflectors in animals using green and gold beetles as contrasting examples. The Journal of Experimental Biology 201: 1307-1313.
- PARKER, A.R., & MCKENZIE, D. (2003): The cause of 50 million-years-old colour. Proceedings of the Royal Society B 270: S151-S153.
- PARTRIDGE, J.C., SHAND, J., SRCHER, S.N., LYTHGOE, J.N., & VAN GRONING-LUYBEN, W.A.H.M. (1989): Interspecific variation in the visual pigments of deep-sea fishes. Journal of Comparative Physiology A, 164: 513-529.
- PASSAMA-VUILLAUME, M., & BARBIER, M. (1966): Sur la biosynthèse de la biliverdine IX α par la mante *Mantis religiosa* et le criquet *Locusta migratoria*. Comptes rendus hebdomadaires des séances de l'Académie des sciences, Série D 263: 924-925.
- PROVENCIO, I., LOEW, E.R., & FOSTER, R.G. (1992): Vitamin A2-based visual pigments in fully terrestrial vertebrates. Vision Research 32: 2201-2208.
- PRZIBAM, H. (1913): Grüne tierische Farbstoffe. Pflügers Archiv für die gesamte Physiologie, 153: 385-400.

- PRZIBRAM, H., & LEDERER, E. (1933): Das Tiergrün der Heuschrecken als Mischung aus. Farbstoffen. Anzeiger der Akademie der Wissenschaften Wien, Mathematisch-Naturwissenschaftliche Klasse 70: 163-167.
- RASCHER, U., NICHOL, C.J., SMALL, C., & HEN-DRICKS, L. (2007): Monitoring spatio-temporal dynamics of photosynthesis with a portable hyperspectral imaging system. Photogrammetric Engineering & Remote Sensing 73: 45-56.
- RASCHER, U., DAMM, A., VAN DER LINDEN, S., OKUJENE, A., PIERUSCHKA, R., SCHICKLING, A., & HOSTERT, P. (2010): Sensing of photsynthetic activity in crops. Pp. 87-99 in: OERKE, E.-C., GERHARDS, R., MENZ, G., & SIKORA, R.A. (eds.): Precision crop protection – The challenge and use of heterogeneity. Springer; Berlin, Den Haag.
- R-DEVELOPMENT-CORE-TEAM (2008): R: A language and environment for statistical computing. R Foundation for Statistical Computing; Vienna. http://www.R-project.org.
- RUDIGER, W. (1970): Animal biliproteins. Proceedings of the 505th Meeting of the Biochemical Society. Biochemical Journal 119 (3): 1P.
- RUTOWSKI, R.L., MACEDONIA, J.M., MOREHOUSE, N., & TAYLOR-TAFT, L. (2005): Pterin pigments amplify iridescent ultraviolet signal in males of the orange sulphur butterfly, *Colias eurytheme*. Proceedings of the Royal Society B 272: 2329-2335.
- SAITO, H. (2001): Blue biliprotein as an effective factor for cryptic colozration in *Rhodinia fugax* larvae. Journal of Insect Physiology 47: 205-212.
- SEAGO, A.E., BRADY, P., VIGNERON, J.P., & SCHULTZ, T.D. (2009): Review: Gold bugs and beyond: a review of iridescence and structural colour mechanisms in beetles (Coleoptera). Journal of the Royal Society Interface 6: 165-184
- SHCHERBAKOV, D., KNÖRZER, A., HILBIG, R., HAAS, U., & BLUM, M. (2012): Near-infrared orientation of Mozambique tilapia *Oreochromis mossambicus*. Zoology 115: 233-238.
- SCHWALM, P., STARRETT, P., & MCDIARMID, R. (1977): Infrared reflectance in leaf-sitting neotropical frogs. Science 196: 1225-1227.
- TANAKA, G., TANIGUCHI, H., MAEDA, H., & NOMURA, S. (2010): Original structural colour preserved in an ancient leaf beetle. Geology 38: 127-130.

- TETLEY, C., & YOUNG, S. (2007): Digital IR and UV imaging. Part 1: Infrared. Journal of Visual Communication in Medicine 30: 162-171.
- TETLEY, C., & YOUNG, S. (2008): Digital infrared and ultraviolet photography using advanced camera services modified equipment. Journal of Visual Communication in Medicine 32: 40-42.
- TRISTAN J.F., & MICHAUD G. (1916): Probable perception of light by some animal species. Scientific American January 15: 81, 88-89.
- VAN DE KAMP, T., & GREVEN, H. (2010): On the architecture of beetle elytra. Entomologie heute 22: 191-204.
- VERHOEVEN, G. (2008): Imaging in invisible using modified digital still cameras for straightforward and low-cost archaeological near-infrared photography. Journal of Archaeological Science 35: 3087-3100.
- VIGNERON, J.P. PASTEELS, J.M., WINDSOR, D.M., VÉRTESY, Z., RASSART, M., SELDRUM, T., DU-MONT, J., DEPARIS, O., LOUSSE, V., BIRO, L.P., ERTZ, D., & WELCH, V. (2007): Switchable reflector in the Panamanian tortoise beetle *Charidotella egregia* (Chrysomelidae: Cassidinae). Physical Review E 76 031901: 1-9.
- VANDERPLANK, FL. (1934): The effect of infrared waves on tawny owls (*Strix aluco*). Proceedings of the Zoological Society of London 104: 505-507.
- VIGNERON, J.-P., & SIMONIS P. (2010): Structural colours. Advances in Insect Physiology 38: 181-218.
- WAGNER, G. (1971): Infrarot-Fotografie Der Weg ins Unsichtbare. 2. Auflage. Verlag die schönen Bücher Dr. Strache KG; Stuttgart.
- WELCH, V., LOUSSE, V., DEPARIS, O., PARKER, A., & & VIGNERON, J. (2007): Orange reflection

from a three-dimensional photonic crystal in the scales of the weevil *Pachyrrhynchus congestus pavonius* (Curculionidae). Physical Review E 75: 41919-1-41919-9.

- WILLIG, A. (1969): Die Carotenoide und der Gallenfarbstoff der Stabheuschrecke, *Carausius morosus*, und ihre Beteiligung an der Entstehung der Farbmodifikationen. Journal of Insect Physiology 15: 1907-1927.
- WOJTUSIAK, R.J. (1947): Investigations on the vision of infra-red in animal. I. Experiments on water tortoises. Bulletin International de l'Academie des Sciences de Cracovie B 2: 43-61
- WOJTUSIAK, R.J. (1949): Polish investigations on homing in birds and their orientation in space. Proceedings of the Linnean Society of London 160: 99-108.
- WOOD, R.W. (1910 a): A new departure in photography. The Century Magazine 79: 565-572.
- WOOD, R.W. (1910 b): Photography by invisible rays. The Photographic Journal 50: 329-338
- Dipl. Biol. Michael Mielewczik
- Dr. Frank Liebisch
- Prof. Dr. Achim Walter
- ETH Zürich
- Institute of Agricultural Sciences
- Universitätstr. 2
- CH-8092 Zürich/Switzerland
- E-Mail: michaemi@ethz.ch
- E-Mail: frank.liebisch@ipw.agrl.ethz.ch
- E-Mail: achim.walter@usys.ethz.ch

Prof. Dr. Hartmut Greven

Zoologie II der Heinrich-Heine-Universität

Universitätsstr. 1

- D-40225 Düsseldorf
- E-Mail: grevenh@uni-duesseldorf.de

Tab. 1: NIR-Reflexion von Insektenarten aus Museumssammlungen basierend auf "Red-Edge"-Fotografie. Die Anzahl der untersuchten Individuen steht in Klammern hinter dem wissenschaftlichen Namen.

| Species | Family | Color (dorsal view) | NIR-reflectance |
|---|-------------|--|---|
| Coleoptera | | | |
| Chryauphi amminitata (Saunders, 1867) (2) West Africa | Buprestidac | Green metallic | No |
| Chryaarpis chongata (Olivier, 1790) (3) Sierra Leone | Buprestidae | Green metallic (red tint) | No |
| Chrysochroa andaimanensis Saunders, 1867 (2) Southeast-Asia | Buprestidae | Green metallic | No |
| Chrystedrna buqueti (Gory, 1833) (1) Malysia, Borneo | Buprestidae | Black with big yellow markings on the elytra | No (black areas) and medium reflectance of the markings |
| Chrystehna drysmu Gory, 1840 (2) Phillippines | Buprestidae | Green metallic | No |
| Chyptochroa athurthi Hope, 1843 (2) India, Thailand | Buprestidae | Metallic dark green with a light yellow stripe on the elytra; pronotum greenish with a strong red metallic tint | Only the yellow parts show a medium to high reflectance |
| Chrystochrae fulminum (Fabricius, 1787) (10) Malysia, Indonesia etc. | Buprestidae | Green metallic | No |
| Chysochraa ignita (Linnacus, 1758) (2) Malaysia, Indochina | Buprestidae | Green metallic | No |
| Chrysodrwa samderri Saunders, 1866 (3) Thailand | Buprestidae | Metallic dark green with a light yellow stripe on the clytra; pronotum greenish with a strong red metallic tint | Only the yellow parts show a medium to high reflectance |
| Chrysodenna alberti Lander, 2000 (1) Asia | Buprestidae | Metallic green | No |
| Chrysodoma aurofoveata Gućrin, 1830 (5) Australia | Buprestidae | Metallic green | No |
| Chrysodema purpurvisentris Deyrolle, 1864 (1) Thailand | Buprestidae | Metallic green | No |
| Chrysodema nuicritrae Landsberg, 1833 (1) Indonesia, Sumatra, Malaysia | Buprestidac | Metallic dark green | No |

Appendix

| Weak to medium (reddish elytra), no (dark pronotum) reflectance beside those of the small specular reflections | Reddish elytra | Buprestidae | Stematers dipsti dipstidits Laporte & Gory, 1837 (3) India |
|---|---|-------------|---|
| Weak to medium (reddish elyrra), no (pronotum), and strong (elyrra) reflectance | Redish elytra with small lighter marking: black pronotum with orange markings | Buprestidae | Sternoera castanca irrgularir (Latreille, 1835) (2) Sudan |
| No (black elytra) and medium reflectance of the yellow markings of elytra and pronorum | Dark clytra with big yellow markings | Buprestidae | Sternoera castanea boucardi Saunders, 1874 (6) Tanzania, Kenya |
| No (green elytra); some specimens with a very weak reflectance of the elytra or medium reflectance of markings on the pronotum | Metallic emerald iridescence | Buprestidae | Sternocera aequisignata Saunders, 1866 (10) India, Thailand |
| No | Metallic green | Buprestidae | Sterasfui squamaa (Klug, 1829) (5) Egypt, Nubia |
| No | Metallic green | Buprestidae | Steraspis subra ((Fabricius, 1775) (3) Senegal |
| No | Metallic green | Buprestidae | Steraphi abusa Harold, 1878 (1) Somalia |
| No | Metallic green ; pronotum red metallic tint | Buprestidae | Sterapiis hreviorniie (Klug, 1835) (5) Senegal |
| No | Metallic green with reddish tint | Buprestidae | Philotteanus maitlandi Lansberge, 1883 (2) Thailand |
| No | Metallic green | Buprestidae | Lampentis fustnosa (Fabricius, 1775) (3) India |
| No (black elytra) and medium reflectance lof the yellow markings of elytra and pronotum | Black elytra and pronotum with yellowt markings | Buprestidae | Juludir nariolaris froggazmeri Mexyer-Darcis, 1883 (6) Turkmenistran |
| No (black elytra) and medium reflectance lof the yellow markings of elytra and pronotum | Black elytra and pronotum with yellowt markings | Buprestidae | Julodis suriolaris burburica (Semencov, 1893) (14) Turkmensitan |
| No (black elytra) and medium reflectance of the yellow markings of elytra and pronorum | Black elytra and pronotum with light markings | Buprestidae | Jubalis sultisollis Laporte & Gory, 1835 (1) Africa |
| No (black elytra) and medium reflectance of the yellow markings of the elytra and pronotum | Black elytra and pronotum with yellow markings | Buprestidae | Jubodis rothii (Sturm, 1843) (1) Palestine |
| No | Metallic green | Buprestidae | Iridotaenia muptuosa (Laporte & Gory, 1835) (2) Indonesia, Sumatra |
| No | Metallic Green | Buprestidae | Einides publivatiris (Laporte & Gory, 1835) (8) Africa |
| No | Metallic Green | Buprestidae | Ender triangularis (Thomson, 1878) (2) Africa |
| Only the orange markings on the clytra show a medium reflectance | Black with numerous orange- brown striped markings | Buprestidae | Cyrioides imperialis (Fabricius, 1801) (5) Australia |

Tab. 1: Continued.Tab. 1: Fortsetzung.

| Sternotera diardii Gory, 1840 (3) | Buprestidae | Metallic green to metallic gold and blue | No |
|--|-------------|--|---|
| Stremorera feldpathias White, 1843 (2) South Africa | Buprestidae | Orange to red (clytra) | Medium (reddish elytra) |
| Stemaera hiddebrauth Harold, 1878 (6) Ethiopia, Kenya, Tanzania | Buprestidae | Reddish brown elytra; black pronotum | Weak to medium (reddish elytra) and no (black pronotum) reflectance |
| Sternoera Inniter Waterhouse, 1898 (1) Somalia, Kenya, Tanzania | Buprestidae | Reddish brown elytra; black pronotum | Weak to medium (reddish elytra) and no (black pronotum), reflectance |
| Sternovera laveigata (Olivier, 1790) (5) | Buprestidae | Dark | No (black elytra) |
| Sternovera stemicornis (Linnacus, 1758) (3) Bengal | Buprestidae | Metallic green, with light yellow markings | No (green elytra) and medium reflectance of the yellow markings of elytra and pronotum |
| Carabus inregularis Fabricius, 1792 (10) Europe | Carabidae | Black with metallic red and green shining | Very weak |
| Carolne stabrout amasiene Ceski, 1927 (2) | Carabidae | Black | No |
| Carabus scobrous audonini Brullé, 1837 (2) | Carabidae | Black with a very weak green metallic shining | No |
| Canabus scalwous cancasians Adams, 1817 (2) | Carabidae | Black with a very weak green metallic shining | No |
| Carabus tashrasu okhicus Motschulsky, 1844 (2) | Carabidae | Black with a very weak green metallic shining | No |
| Carubus scabrosus Olivier, 1795 (3) | Carabidae | Black with a very weak blue metallic shining | No |
| Carabus scabrosus sommeri Mannerheim, 1844 (2) | Carabidae | Black with a very weak blue metallic shining | No |
| Canabus scabrans taurias Bonell, 1810 (2) Crimia, Ukraine | Carabidae | Black with a very weak green metallic shining | No |
| Carribus statbraus transversalis Csilsi, 1927 (2) | Carabidae | Black | No |
| Carabus griacus Kollar, 1843 (2) Israel | Carabidae | Black | No |
| Carabus (Proems) gigas Creutzer, 1799 (4) Europa | Carabidae | Black | No |
| Carehas (Procretes) anatolicus anatolicus Chaudoit, 1857 (2) | Carabidae | Black | No |
| Carabus (Prorrustes) cherevolati Cristoforis & Jan, 1837 (2) Turkey, SW-Georgia | Carabidae | Black | No |

| Continued. | Fortsetzung. |
|------------|--------------|
| ÷ | ÷ |
| Tab. | Tab. |

| No | Black | Geotrupidae | Geotrapes pyremaeae (Charpentiet, 1825) (9) Europe |
|--|---|--------------|--|
| Weak to medium reflectance of the yellowish markings | Black with yellowish markings on the clytra and pronotum | Elateridae | Tetrabbus flubellisornis (Linnaeus, 1758) (2) South Africa |
| No (black parts) and medium to high (orange parts) of the body reflectance | Orange with black stripes on the elytra; orange black markings on the pronotum | Elateridae | Semioins intermedius (Hechset, 1806) (3) Brazil |
| High reflectance only of the elytra,the pronouum and the , reddish stripe | Orange elytra and pronorum; black spors and a long, reddish stripe in the middle of the head, framed by two dark stripes | Elateridae | Semiona imperialis (Gueim-Meneille, 1844) (3) Peru, Colombia, Venezuela |
| Weak (brown parts) and weak to medium (orange parts) reflectance | Orange with brownish stripes | Elateridae | Semiona distinctus Hechss, 1806 (3) Brazil, Paraguay, Argentina |
| Medium (pronouum, elytra) and high (spots) reflectance | Brown with two small bioluminescent spots on the pronotum | Elateridae | Pyrghams phoghansens: Laporte, 1840 (2) Trinidad, Tobago |
| No (black elytra) and high reflectance of the yellow markings of elytra and pronorum | Black elytra; pronotum with light yellow markings | Elateridae | Chaladpidius genatus Eschscholtz, 1829 (2) South America |
| No to very weak | Golden bown with greenish tint | Elateridac | Camposternus anratus (Drury, 1773) (2) China |
| Weak | Brownish | Elateridae | Agopting farapes Fileuriaux, 1947 (2) South Asia |
| No (dark spors) and medium reflectance of elyrra and pronotum | Brownish elytra; pronorum with dark spots | Elateridae | Alam larteur Candeze, 1857 (2) Philippines, Borneo erc. |
| Veryweak | Dark brown to black | Dynastidae | Orgetes boust (Fabricius, 1777) (3) |
| V cry weak | Dark brown to black | Dynastidae | Bothynus ametador (Mannecheim, 1829) (2) Neotropis |
| Weak reflectance and medium (orange stripe) reflectance | Dark metallic with orange stripe on the elytra | Cetoniidae | Plastiorthina cincta Allard, 1991 (4) Africa |
| The green metallic coloration and the orange markings appear light to medium blue, but the IR channel alone shows a weak to medium reflectance of the orange markings and the green antennas | Green metallic with orange markings on elytra and pronotum | Cerambycidae | Sternotomic behemuni (Chevrolat, 1844) (1) South Africa |
| No | Black | Carabidae | Carubus (Prverates) coriaceus Linnacus, 1758 (2) Europa |
| No | Black | Carabidae | Curvibus (Programs) differentia Adams, 1817 (2) |

| Continued. | Fortsetzung |
|------------|-------------|
| ÷ | ÷ |
| Tab. | Tab. |

| No | No | No | Weak (abdomen) 222222 | Weak | Weak to medium | Some specimens show no or a very weak reflectance, others a medium reflectance of elytra and pronoum | Medium to high reflectance only of the yellow markings | Medium reflectance only of the yellow markings | Weak to medium reflectance except the black stripes and points | No | Weak to medium refeterance of the elytra. The pronotum appeared somehow darker. | Very weak reflectance of the elytra. Nearly no reflectance of the pronorum. | No (point matkings), medium (elytra, legs) a nd weak to medium (pronotum) reflectance. | Only the yellow parts of the elytra show a medium reflectance | Only the light brown areshow a medium reflectance | No |
|---|---|--|--|---|--|--|---|--|--|---|--|---|---|---|---|---|
| Black | Black | Very dark, metallic green | Brown abdomen with black head | Metallic | Metallic green to metallic brown | Metallic green; olive | Black with yellow point markings on the elytra; yellow markings on the pronotum | Black with numerous yellow stripes and markings | Dark reddish -brown with large orange stripes at the side. Inside the stripes black points | Light green | Light brown | Red brown | Orange elytra with black point markings; pronotum olive metallic green with red tint. Legs red brown | Black markings on yellow ground | Light brown elytra with dark stripes | Very dark to black |
| Geotrupidae | Histeridae | Lucanidae | Scarabaeidae | Scarabaeidae | Scarabaeidae | Scarabacidae | Scarabaeidae | Scarabacidae | Scarabaeidae | Scarabacidae | Scarabaeidae | Scarabaeidae | Scarabaeidae | Scarabaeidae | Scarabaeidae | Scarabaeidae |
| Geotrupes wernalise (Liamacus, 1758) (10) Europe, Asia Minor | Atholus duodecimistriotus (Schrank, 1781) (4) Europe | Lumprinu alabhinar (Gestro, 1875) (1) Indonesia, New Guinea | Anomula geominula Arrow, 1912 (2) South India | Anghognathus paradus (Donovan, 1805) (1) Australia | Anophognations windiaments Waterbouse, 1873 (1) Australia | Caelorrhina saperba Gerstäcker, 1883 (5) Tanzania | Chrimlatia hurkei Westwood, 1843 (1) South Africa | Chelorthina sanggei (Hatris, 1844) (1) Zaire, Congo | Chondrorthing picturata (Harold, 1878) (1) Central Africa | Chrysina maraput Francillon, 1795 (1) Mexico | Dicrumorphulus bouringi Pascoc, 1863 (3) China | Diplognatha gogarer Forster, 1771 (1) Africa | Endietha smithi (MacLeay, 1838) (1) Central-, West-, and East Africa | Pachnoda inaripat (Gory & Percheron, 1833) (1) Africa | Gnathoren hilmean Kraatz, 1886 (1) tropical Africa | Holioopris gigar Linnacus, 1758 (1) Africa |

| Very weak | Green with orange tint | Scarabaeidae | Pychodesther gratiosa (Ancey, 1881) (6) Tanzania |
|---|--|--------------|--|
| Weak metallic | Light metallic green | Scarabaeidae | Plusintis (Chiyaina) rephendens (Boucard, 1875) (1) Costa Rica, Panama |
| Weak metallic | Vividly green | Scarabaeidae | Plusiotis (Chrysing) gloriosa (LeConte, 1854) (1) USA |
| Weak metallic | Golden with greenish tint | Scarabaeidae | Pluiotis batesi Boucard, 1875 (1) Central America |
| No (body) and weak (reddish stripe, greenish indiscence) reflectance | Black with reddish stripe and greenish iridiscence at the end of the abdomen | Scarabaeidae | Phanana (Sulaphanna) impenator Chevrolat, 1844 (1), Bolivia, Paraguay |
| No | Dark green | Scarabaeidae | Phamaeus (Sukophamaeus) amrioulits (Harold, 1880) (1) Columbia, Venezuela |
| Medium | Yellow green metallic | Scarabacidae | Phadimur inemi Moser, 1926 (1) Southern America |
| No | Metallic green (red tint) | Scarabacidac | Pelidnota sumptuosa Vigors, 1825 (1) Southern America |
| No to very weak reflectance | Dark metallic green | Scarabacidae | Peliduota yamitarsis Gory, 1833 (1) Southern America |
| No (black parts) and medium (yellow parts) reflectance | Black with yellow markings | Scarabaeidae | Pachnoda sinuata Harold, 1878 (2) Africa |
| Very weak reflectance of the dark body part and medium to high reflectance of the the orange markings | Dark-brown with orange markings on the elytra and pronotum | Scarabaeidae | Pathmoda surigory (Gory & Percheron , 1833) (1) Africa |
| No (black elytra) and mediumreflectance of the orange markings | Black with large orange markings on the elytra | Scarabacidae | Pachnoda poggei (Harold, 1878) (3) Africa |
| No | Dark green | Scarabaeidae | Oxysternum conspicit/atum (Weber, 1801) (2) Ecuador |
| Generally weak, but weak to medium (lighter markings at the side) reflectance. | Brown with black markings and black legs | Scarabaeidae | Miarposcila cincta (Goty & Percheron, 1833) (1) Australia |
| Nearly no reflectance | Green to brown | Scarabaeidae | Megmorbina torquata (Drury, 1782) (1) West Africa |
| Nearly no reflectance | Green | Scarabacidae | Ischiospha Incironzes Krautz, 1890 (13) Australian region |
| Very weak reflectance of the elytra. | Dark green | Scarabaeidae | Heterorrhina obeaa Janson, 1884 (3) India |
| Nearly no reflectance | Emerald metallic green | Scarabacidac | Heterorbina elegans (Fabricius, 1781) (1) South India |

| Continued. | Fortsetzung |
|------------|-------------|
| ÷ | ÷ |
| Tab. | Tab. |

| No (black areas) and relatively high (wings) reflectance; wings totall | Metallic black green with dark | Sphecidae | Chlorion aerarium Patton, 1879 |
|--|---|--------------|--|
| No (black areas) and relatively high (wings) reflectance; wings totall opaque to the blue part of the spectrum | Black with reddish wings | Pompilidae | Pqnir sp. (2) USA |
| | | | Hymenoptera |
| Medium (yellow markings) and no (black areas) reflectance | Black, with very fine yellow markings | Pentatomidae | Trochizocoris rutundatus Horvath, 1895 (1) Palacarctic Region |
| Medium (red and yellow markings) and no (black areas) reflectance | Black with red and yellow markings | Pentatomidae | Steneggun coloratum (Klug, 1845) (1) Europe |
| High | Green | Pentatomidae | Negura wirdula (Linnacus, 1758) (24) cosmopolit |
| Medium; black markings no) | Green with black markings | Pentatomidae | Palomena viridistima (Limnacus, 1761) (30) Europe |
| Weak to medium; black stripes no reflectance | Green with black stripes | Pentatomidae | Palomena prazina (Linnacus, 1761) (18) Europe |
| Weak | Olive green | Pentatomidae | Chloredroa pinicola (Mulsant & Rey, 1852) (18) Europe |
| Weak (a few specimens medium) | Green | Pentatomidae | Chloredhna juniperina (22) Europe |
| Weak to medium; black stripes no reflectance | Light brown with black markings | Pentatomidae | Hologanter exilis Horvath, 1903 (1) Europe |
| Weak to medium; black stripes no reflectance | Light brown with black markings | Pentatomidae | Hologaster fibulata (Germar, 1831) (16) Europe |
| Weak | Light brown | Pentatomidae | Dofywris peniellatus Horvach, 1903 (2) Europe |
| No to very weak; reddish parts with weak reflectance | Brown | Pentatomidae | Dofywri: barannw (Linnacus, 1758) (32) Europe to Asia |
| | | | Hemiptera (Heteroptera) |
| Not to very weak | Green to brown | Scarabaeidae | Trigonophorna delesserti (Guérin-Méneville, 1839) (2) India |
| No (elytra), weak (orange markings) and high (white points) reflecta | Emerald elytra and pronotum; elytr with additional orange markings and white points | Scarabaeidae | Stephanorrhina guttata Olivier, 1789 (8) Southeast Africa |
| Medium NIR reflectance | Emerald green | Scarabacidae | Smaragelesthes africana (Drury, 1773) (6) Africa |
| The green elytra show only a Weak reflectance (elytra) and weak to medium (orange color markings) reflectance | Metallic green elytra; orange color markings at the caput | Scarabaeidae | Runda Jana Weber, 1801 (1) Central-America |
| | | | |

lcc

| .1: Continu | .1: Fortsetz |
|-------------|--------------|
| ab. | ab. |

| Polistic biglumic (Linnacus, 1758) (5) North-Africa, South- and Middle-Europe | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
|--|--------------|--|--|
| Politids nimpla (Christ, 1791) (1) South and Middle Europe | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Vepa (Doliobovepula) adulterina (du Buysson, 1905) (3) Europe, Japan, North America | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Vepa craba Linnacus, 1758 (1) Europe | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Vegoa (Vegoula) germanica (Fabricius, 1793) (10) Europe, Asia, Africa | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Verpa orientalis Linnacus, 1771 (1) South Europe | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Vegou nyla (Linnacus, 1758) (10) Holarctis | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Verpa (Dolichorecpula) saxonita Fabricius, 1793 (2) Middle Europe | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Verpa (Dolithorecpula) gylvestris (Scopoli, 1763) (4) Europe, Central Asia etc. | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Verparulgarie (Limnacus, 1758) (23) Eurasia | Vespidae | Yellow / black | No (black parts) and medium (yellow parts, wings) reflectance |
| Lepidoptera | | | |
| Endromis versiooobra (Linnaeus, 1758) (caterpillar) (1) Palearctis | Endromidae | Green | Medium |
| Saturnia pavonia (Linnacus, 1758) (caterpillar) (1) Europe | Saturniidae | Green with black stripes | Medium; stripes no |
| Emomos adniaria (Linnacus, 1758) (4) Europe | Geometridae | Light yellow brown | Medium |
| Emomos ensia (Denis & Schiftermüller, 1775) (4) Europe | Geometridae | Light yellow brown | Medium |
| Cymothoe coacinata (Hewisson, 1874) (3) Central Africa | Nymphalidae | Orange | Medium to High |
| Prepona chromur (Gérin-Ménéville, 1844) (1) South America | Nymphalidae | Dark brown with light blue spots | Weak to medium (wings); spotks slightly stronger |
| Papilio eudoenor Guérin-Menéville, 1829 (1) Papua New Guinea, Sumatra, Sulawesi | Papilionidae | Dark brown with a large yellow patterns on the wings | Weak (dark areas) and medium (yellow markings) reflectance |
| Papilo furie Linnacus, 1758 (1) South Asia | Papilionidae | Very dark metallic green to black wings with light blue markings | Generelly very weak NJR reflectance, weak to medium NJR reflectance in blue spots |

| 1: Continu | 1: Fortsetz |
|------------|-------------|
| p. | p. |

| 0 | | | |
|--|--------------|---|--|
| Trinopalpus imperialis Hope, 1843 (1) Nepal, India, Vietnam | Papilionidae | Green with very large orange markings on the forewings and yellow markings on the back wings | No (green indiscent areas), weak to medium(orange mark (yellow areas) reflectance |
| Troidar priamu (Male) (Linnacus, 1758) (3) Australia, New Guinea | Papilionidae | Green/Black wings with small yellow spots and a yellow abdomen | No (black and green elements) and medium (yellow spot reflectance |
| Mantodea | 1 | | |
| Aanthofty faltataria Goeze, 1778 (3) South America | Mantidae | Dark brown | Weak |
| Chornadadis rhombiadlis (Latreille, 1833) (3) South America | Mantidae | Green / Yellow | Medium to high |
| Dempharys dusinanta Beiter, 1935 (2) Borneo, Indonesien, Malaysia | Mantidac | Dark brown | Weak |
| Derophaya aicajohum (Saussure, 1870) (2) Asia | Mantidae | Deep dark brown | Very weak to weak. Lighter specimens weak to r |
| Derpharys trumata (Guèrin-Menéville, 1843) (2) Asia | Mantidae | Brown to dark brown. Rear wings show large dark brown to black markings | Medium;the dark spots on the rear wings |
| Devplays trigonalers (Westwood, 1889) (2) Asia | Mantidae | Whitish brown to brown | Medium (like leaf litter; in a darker specimen slight |
| Orthodera ministralis (Fabricius, 1775) (3) Australia | Mantidae | Green (light brown); colours were clearly faded | Medium |
| Stagmataptera prearia (Limnacus, 1758) (3) Southern America | Mantidac) | Faded light yellow green to light brown | Medium (body, forewings, yellow markings on the rear somwhat lower |
| Trapidomantis tenera Stal, 1860 (5) Thailand, Malaysia, Borneo etc. | Mantidae | Whitish transparent | very high |
| Odonata | | | |

to medium(orange markings) and strong

nd medium (yellow spots and abdomen)

Weak (dark brown body parts), weak to medium (light brown parts) and medium reflectance (yellow spots)

Brown abdomen with yellow Metallic dark blue; green

Calopterygidae

Libellulidae Libellulidae

> Libellula quadrimaculata (male) (Linnacus, 1758) Orthothrum cancellatum (male) (Linnaeus, 1758)

(1) palearctic distibution (1) Holarcus (1) Europe

Libellula depressa (female) (Linnacus, 1758) Calopterys splendens (Harris, 1782) (1) palearctic distribution

patches coloration

Brownish abdomen Blueish abdomen

Libellulidae

No

Very weak

Weak

ow markings on the rear wings), body

darker specimen slightly reduced

ter specimens weak to medium

| Continued. | Fortsetzung. |
|------------|--------------|
| ÷ | ÷ |
| Tab. | Tab. |

| Orthoptera | | | |
|--|-----------------|---|--|
| Connephains longips (Redtenbacher, 1891) (4) Southern America | Tettigoniidae | Greenish and yellow brown specimens | Medium |
| Enconocphalue invaly-ciphus (Redtenbacher, 1891) (4) China | Tettigoniidae | Green/Yellow-brown | Medium |
| <i>Euronorghalur gracifis</i> (Redtenbacher, 1891) (8) Southeast Asia | Tettigoniidae | Greenish and yellow brown specimens | Medium |
| Euconocphalus indicas (Redtenbacher, 1891) (4) India | Tettigoniidae | Yellow and green specimens | Medium |
| Neormorphalns hrumneri (Redtenbacher, 1891) (4) Southern America | Tettigoniidae | Green/Yellow | Medium to High |
| Neconocphalus occilentalis (Saussare, 1859) (4) Central America | Tettigoniidae | Yellow/brown | Weak |
| Nowworphysise processes (Rediterbacher, 1891) (8) Southern America (Brazil) | Tertigoriidae | Medium brown | Weak to mechum |
| Neurosciphadar Janosiptor (Realicabachier, 1891) (4) Central America | Tettigonidae | Yellow | Weak to Mechan |
| Newworkholder trigge (Linnacus, 1758) (1) North and Central America | Tettigoniidae | Darker yellow/brown | Medium |
| Noncomophydia revála (Rediculacher, 1891) (4) South America | Tenigonidae | Green to yellow/brown | Medium |
| Rogodiu different (Sceville, 1838) (2) Africa | Tettigoniidar | Medium brown | Weak |
| Phonempheres foliosis (Poda, 1761) (31) Middle Fiarrope | Phanenopteridae | Green and light brown specimens | Medium to high also the green forcetings |
| Pleasantytera nasar (Ficher, 1853) (26) North Africa, Benelus | Phanenopteridae | Green and light hrown specimens | Medium to high |
| Phasmatodea | | ALCO DESIGNATION OF | |
| Europronom recutation (Servelle, 1838) (2) Southerset-Avia | Phasmatosica | Big green specimens and smaller brownish specimens | Medium to high (green forewings of the big specimens), weak to medium (smaller specimens) |

| Structure | Family | Order | Color | NIR-selectance |
|--|-------------------|-------------|--|---|
| Lepidoptera | - | | | |
| Attacas atlar (Linnacus, 1758) (caternillar) Southeast Asia | Saturniidae | Lepidoptera | Green with whitish cover | High to very high |
| Mantodea | | | | |
| Conglue goughoder (Linnacus, 1758) Southerset Asis (Tadio Tree: Sei Lanks (Theiland) | Empusidae | Mantodea | Light to dark brown | Weak (comparable to leaves) |
| Mantin religious Janna 1758) Mantin religious (Trimerus, 1758) | Mantidae | Mantodea | Green | High |
| Sphoshnammitic nividii: (Foreskall, 1775) ? Africa | Mantidac | Mantodea | Green | High |
| Orthoptera | | | | |
| Angletha finettana (Fabricius, 1793) (adult) Malaysia | Tettigoniidae | Orthoptera | Green with dark markings | Vcry high |
| Angletha fenetratar (Fabricius, 1793) (juverile nymphs) Malaysia | "l'ettigoniidae | Orthoptera | Green with dark markings | Very high |
| Stiftynochionz coulonizma (Saussure, 1861) (adult) Middle America, Florida | Tettigoniidae | Orthoptera | Green | Vcry high |
| Shiftmachiora contoniana. (Saussure, 1861) (nymph) Middle America, Plonida | Tettigoniidae | Orthoptera | Green | Vcry high |
| Schüheara grogenia Foreskal, 1775 (adult) Africa, Middle East, Asia | Acrididae | Orthoptera | Yellow or green to olive with dark markings | High to very high; dark pattern no; sexual colour dimorphism (!) |
| Schütharnas gregarta Foreskal, 1775 (juvernile nymphs) Africa, Middle East, Asia | Acrididae | Orthoptera | Yellow/green with big black markings | High to very high ; no dark patterns |
| Solutioerus grgsmia Froeskalt, 1775 (voung nymphs) Africa, Middle East, Asia | Acrididae | Orthoptera | Black with yellow eyes | Nearly no (nymphs) reflectance |
| Trophilarri anliari (Stoll, 1813) South-America | Romaleidae | Orthoptera | Green with reddish tint and light brown wings | High |
| Phasmatodea | | | | |
| Hattropteys allatata (Parkinson, 1798) Malaysia, Thailand | Heteropterygidae | Phasmatodea | Green | Very high near infrared reflectance |
| Diapherula: gigunta (fermule) (Gmelin 1789) Middle America | Phasmatidae | Phasmatodea | Green | Very high |
| Escatanonua tiaratum (MacLeay, 1827) Australia | Phasmatidac | Phasmatodea | Green to brown | Medium to high |
| Lambada havi horberti Günther, 1930 Southeast-Asia | Phasmatidae | Phasmatodea | Brownish-green | Medium (comparable to twigs) |
| Megarania hateai (Kithy, 1896) Australia, New-Guinea, Solomon Ishanda, Phillipines etc. | Phasmatidac | Phasmatodea | Brown with bluish-green legs | Weak, the blue-green legs show a medium to high reflectance |
| Medauroidea estradoritata (Brunner von Watteneyl, 1907) Vietnam | Phasmatidae | Phasmatodea | Brown | Weak to medium near (comparable to twigs) |
| Plyllium celoium de Haan, 1842 Sulawesi, Ambon | Phyllidae | Phasmatodea | Green / yellow | Very high |
| Parybauma admitri Conle & Hennemann, 2005 Peru | Pseudophasmatidae | Phasmatodea | Black with yellow eyes | Very low (body; overall reflectance including the spectral range of NIR) |

Tab. 2: NIR-reflectance of living insects as estimated by Red-Edge-Photography. **Tab. 2:** NIR-Reflexion von lebenden Insekten basierend auf "Red-Edge"-Fotografie.

ZOBODAT - www.zobodat.at

Zoologisch-Botanische Datenbank/Zoological-Botanical Database

Digitale Literatur/Digital Literature

Zeitschrift/Journal: Entomologie heute

Jahr/Year: 2012

Band/Volume: 24

Autor(en)/Author(s): Mielewczik Michael, Liebisch Frank, Walter Achim, Greven Hartmut

Artikel/Article: <u>Near-Infrared (NIR)-Reflectance in Insects – Phenetic Studies of</u> <u>181 Species. Infrarot (NIR)-Reflexion bei Insekten – phänetische</u> <u>Untersuchungen an 181 Arten 183-216</u>