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

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

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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 NDVI-photographs), 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-non-reflecting 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).

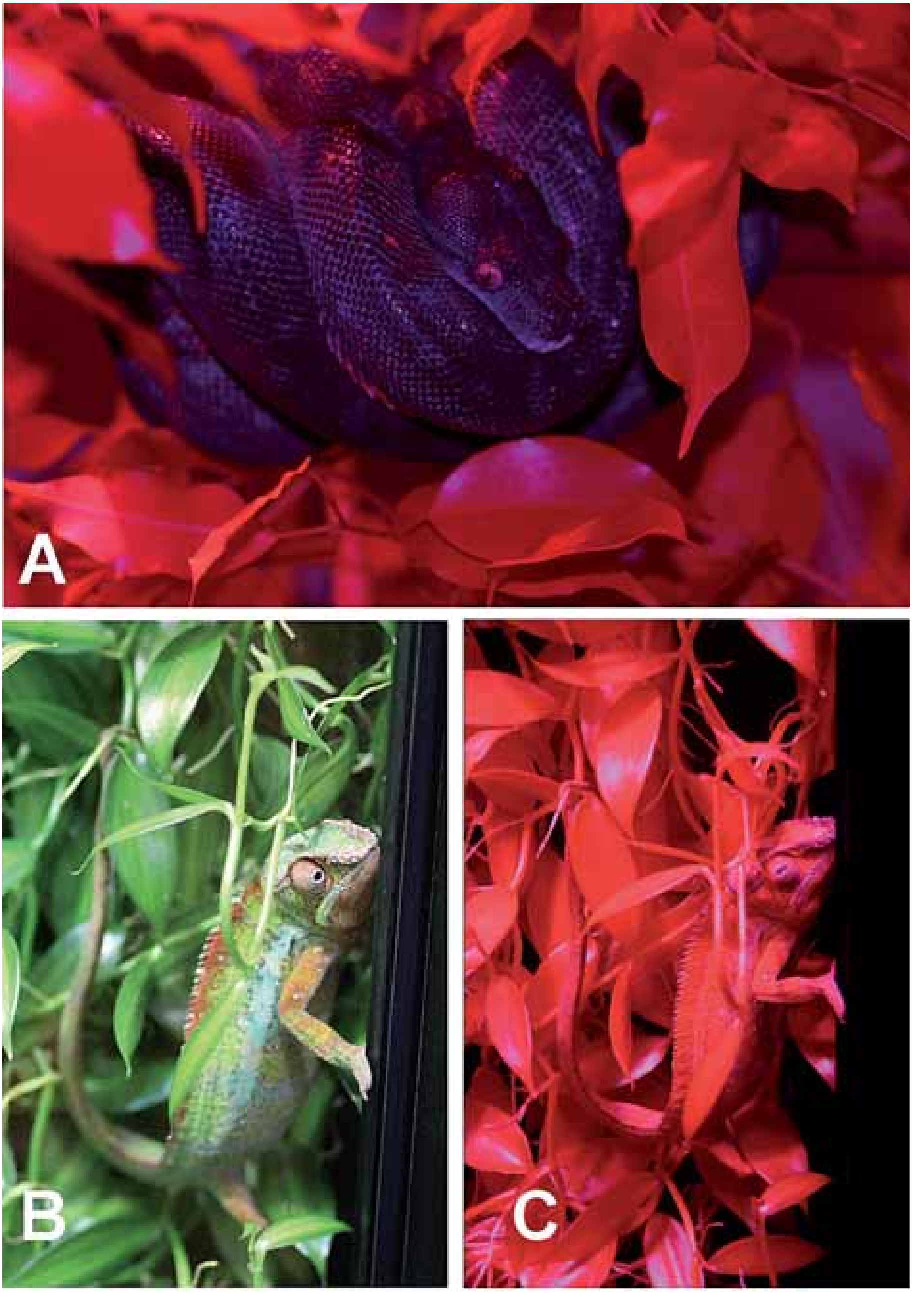


Fig. 1: The NDVI-camera clearly shows reflectance differences in the NIR. Contrary to the green tree python *Morelia viridis* (**A**), the green panther chameleon *Furcifer pardalis* (**B**) shows a high NIR-reflectance, which is comparable to that of green coloured leaves (**C**).
Abb. 1: Die NDVI-Kamera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

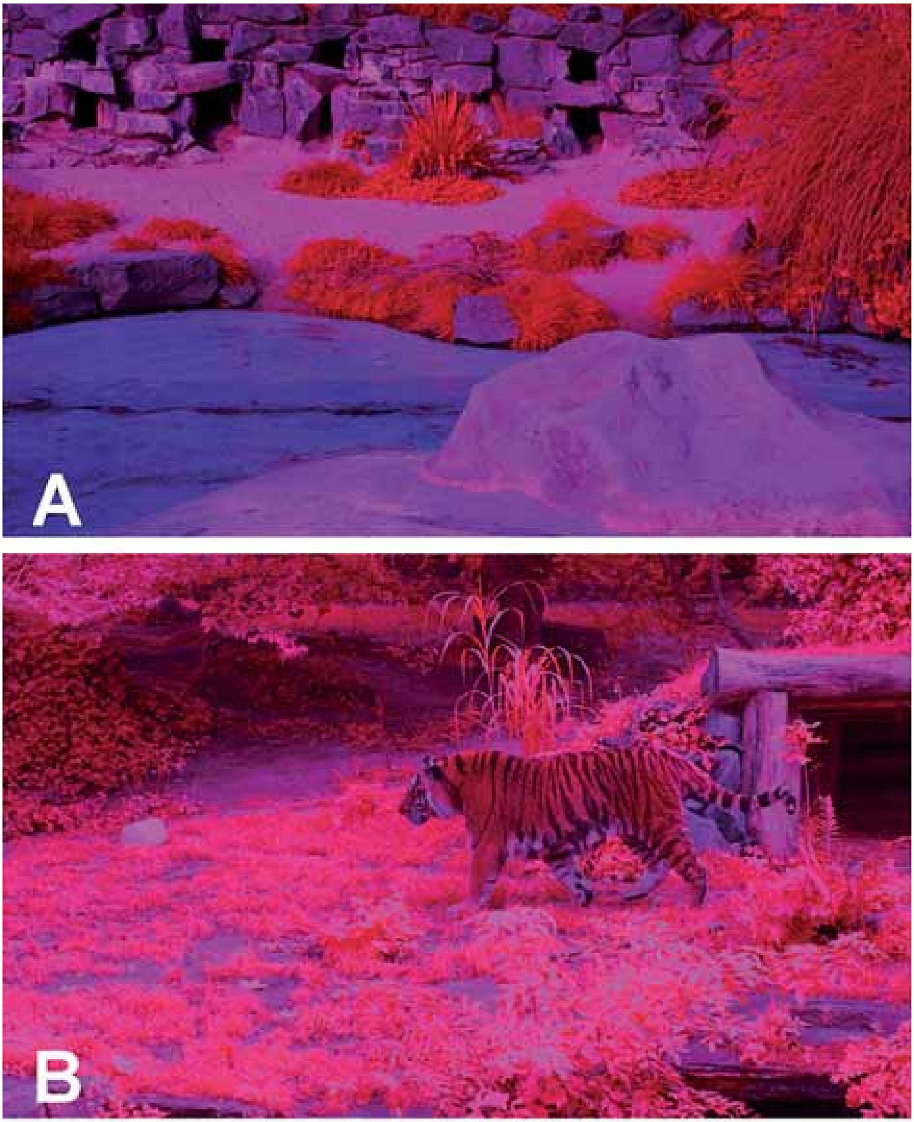


Fig. 2: Colour rendering of the infrared sensitive NDVI-camera. **A** Landscape with different materials. Vegetation appears pink to light red (high NIR-reflectance), stones and sand are violet to blue (low NIR-reflectance). **B** Depending on shadow, illumination, kind of leaves and light quality, vegetation 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-colour-infrared photography (for comparisons see GIBSON 1978).

3.2. NIR-reflectance in insects

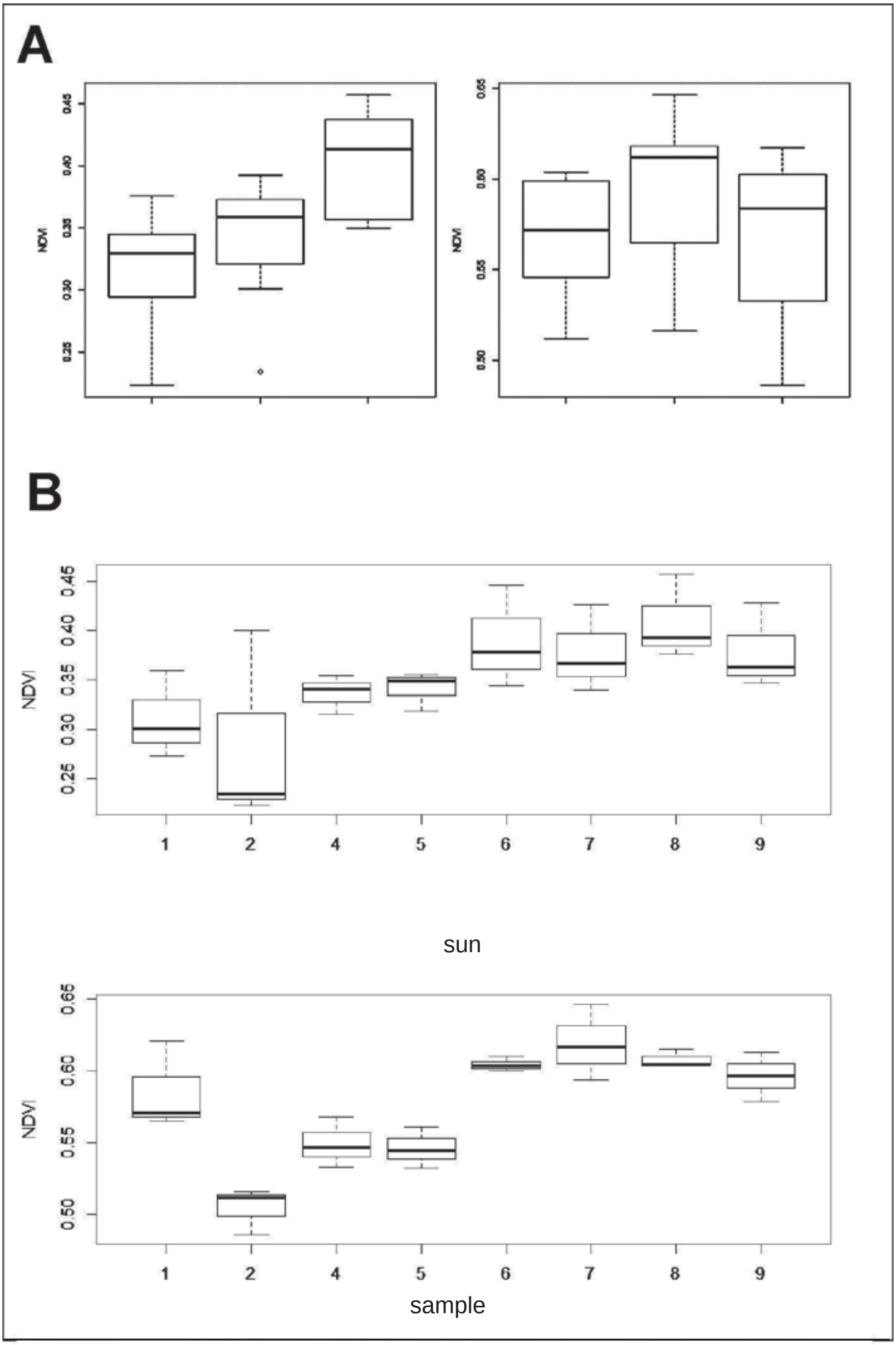
Generally, our NIR-images reveal a remarkable variation not only concerning the occurrence of NIR-reflectance, but also concerning the reflectance patterns (for an overview see Tabs. 1, 2; Figs. 4-10). Only for description we herein use five categories to characterize reflectance: no, very weak, weak,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

3.2 1. 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 dark-brown 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.

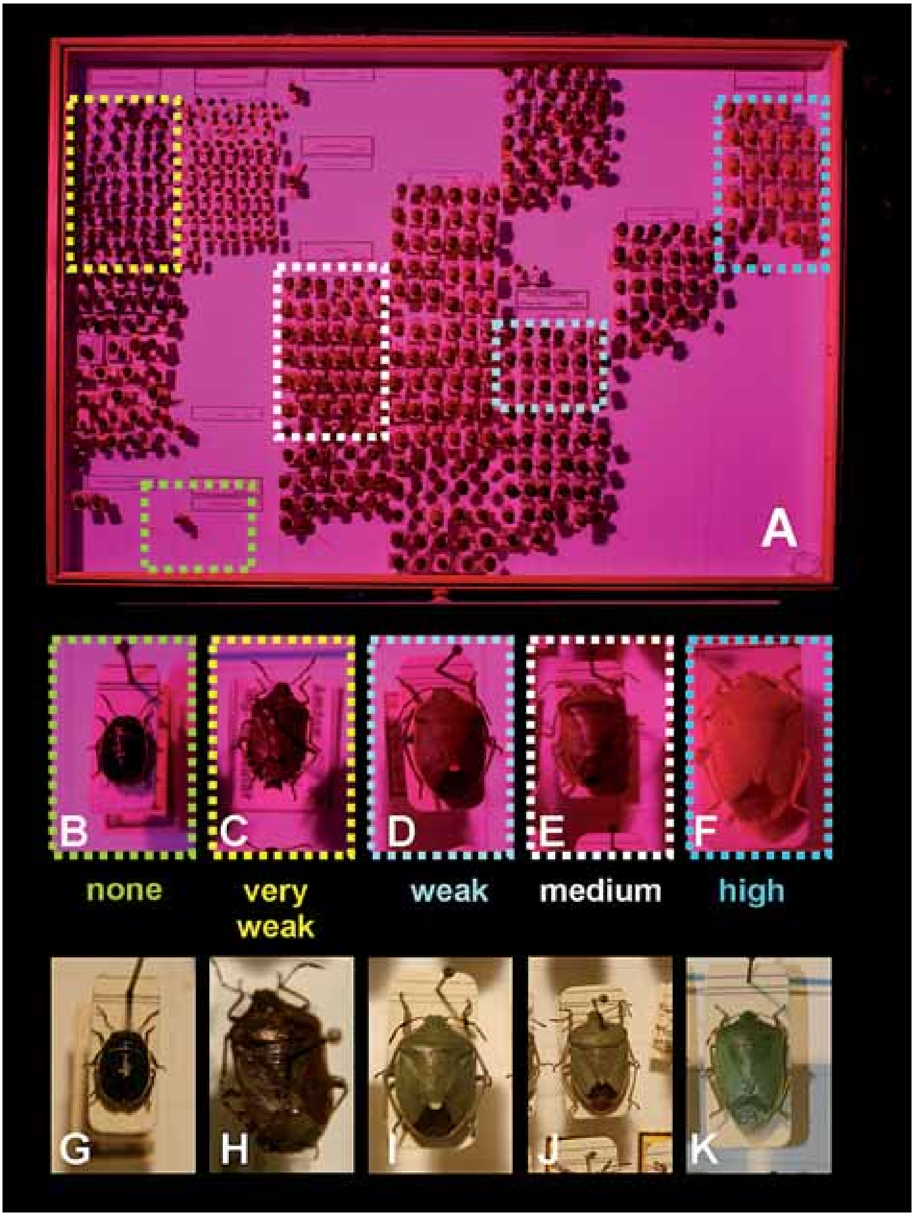


Fig. 4: Different Pentatomidae species in a showcase. Overview (**A**) and NIR (**B-F**) and conventional color photos (**G-K**) of selected species, which either do not reflect NIR (**B**) or reflect (**C**) very weak, (**D**) weak , (**E**) with medium intensity and (**F**) high. (**B+G**) *Trochycocoris 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**) *Trochycocoris 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-

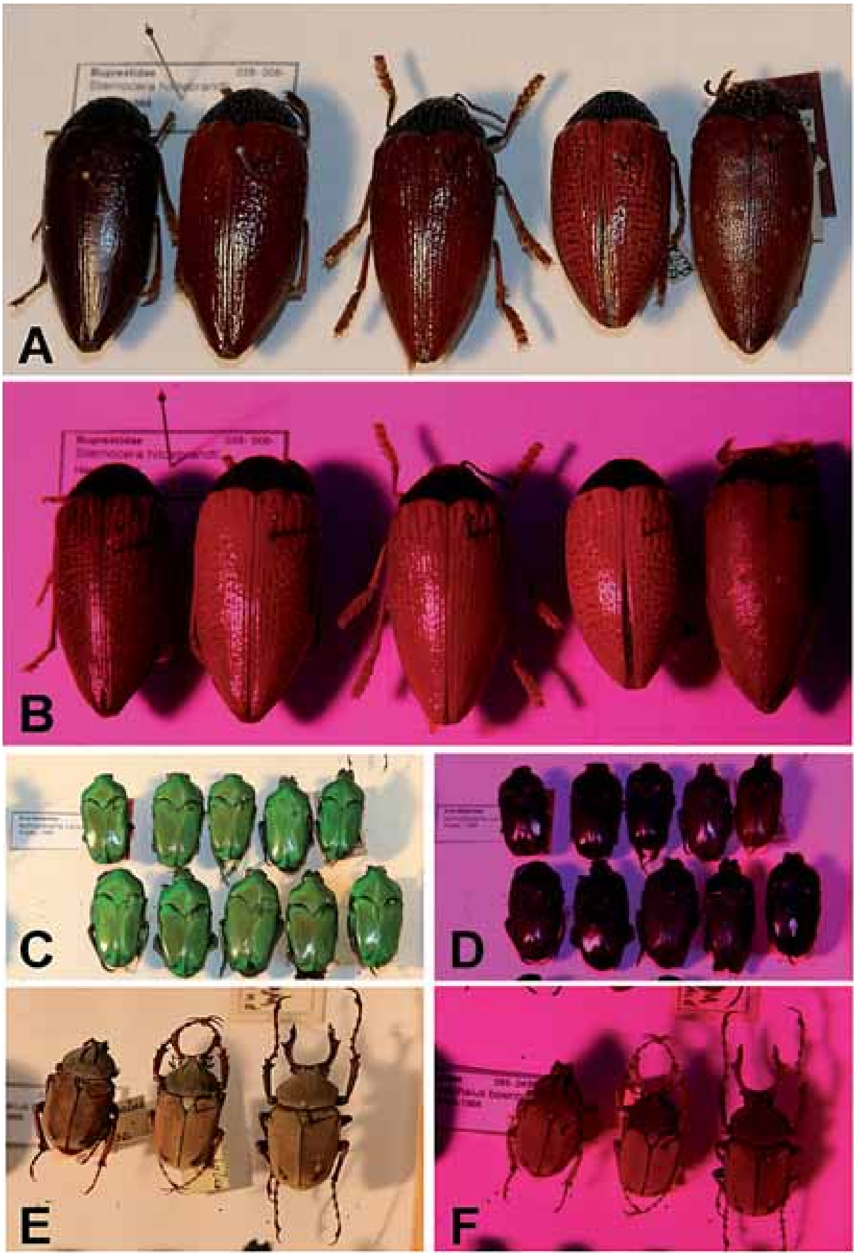


Fig. 5: Specimens of different beetle species shown in conventional colour (**A,C,E**) and NIR-photos (**B,D,F**). The brown to red brown jewel beetle *Sternocera hildebrandti* (**A+B**) shows a medium NIR-reflectance, as the light brown elytra of the stag beetle *Dicranocephalus bowringi* (**E+F**). 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.

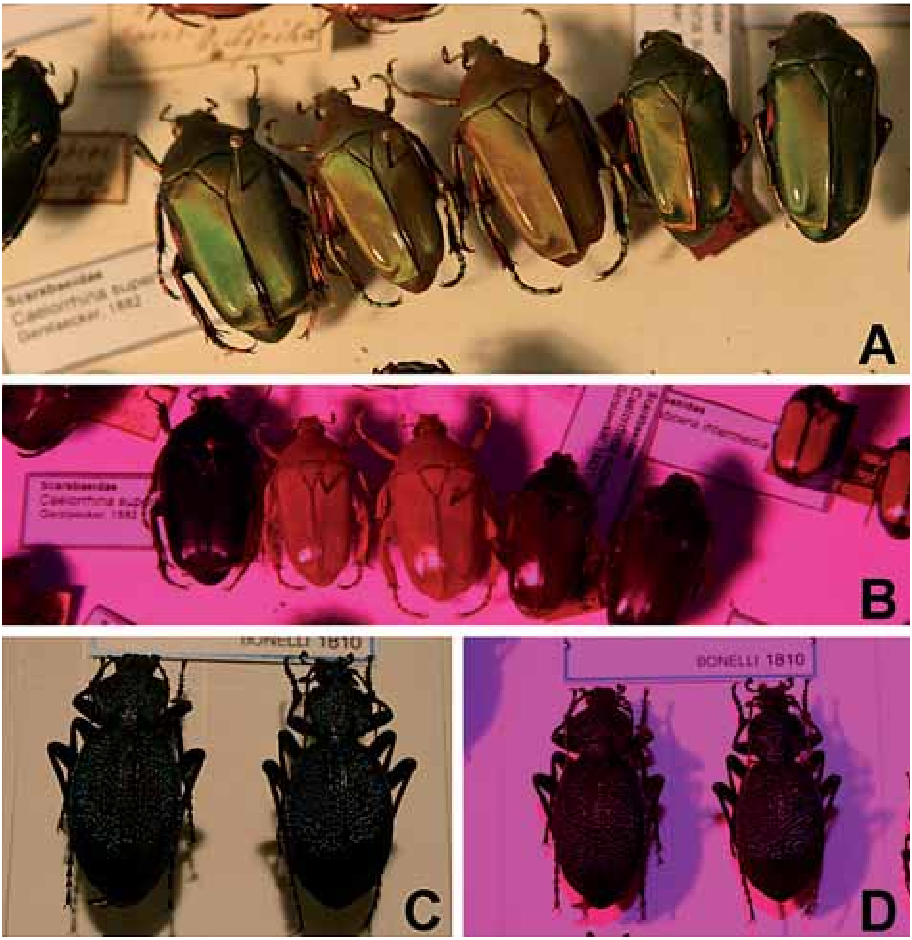


Fig. 6: Specimens of the rose chafer *Caelorrhina superba* (**A**) differ considerably concerning NIR-reflectance (**B**). Black beetles such as *Carabus scabrosus tauricus* (**C**) generally do not show NIR-reflectance (**D**).

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,

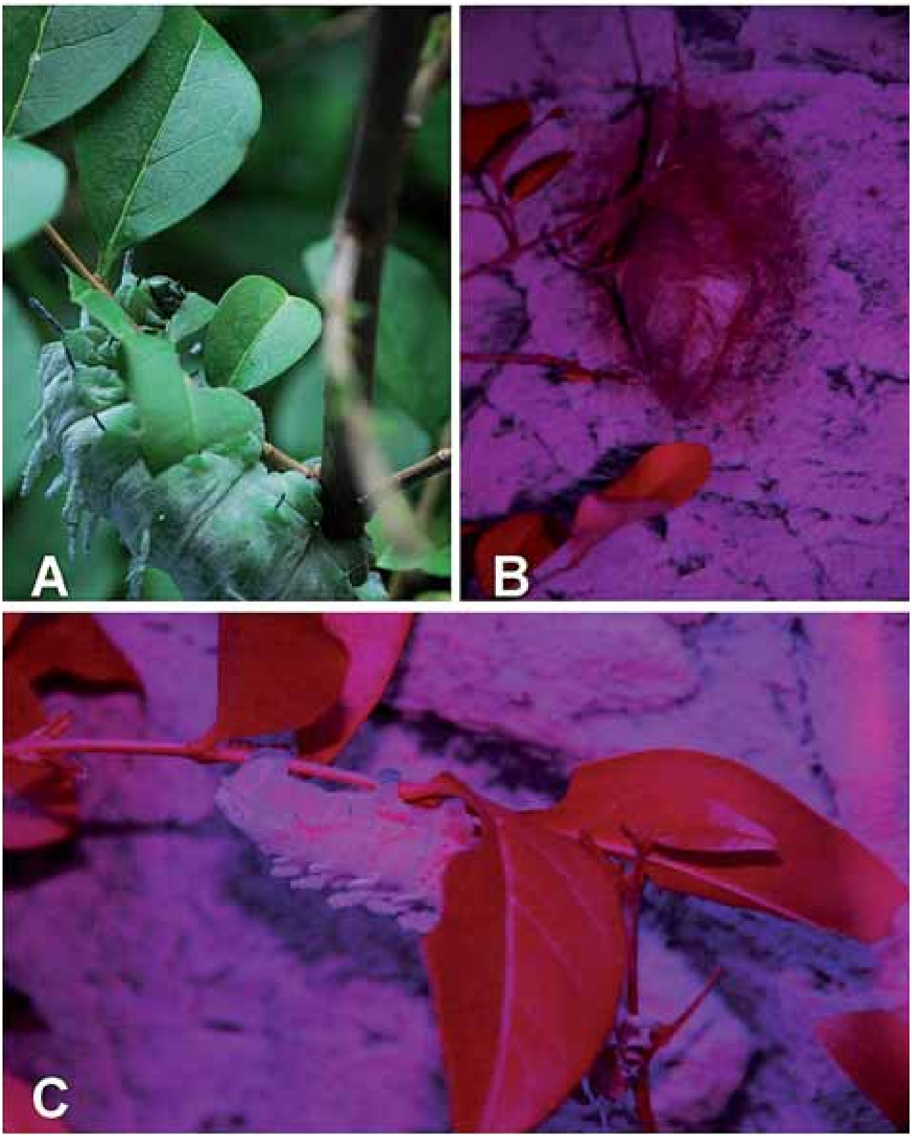


Fig. 7: The bluish-green caterpillar of the Atlas moth *Attlacus atlas* (**A**) exhibits a high NIR-reflectance (**C**), which markedly differs from that of the leaves because of its high blue light reflection. The seemingly higher NIR-reflectance of the leaves is caused by their low blue light reflectance. 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**).

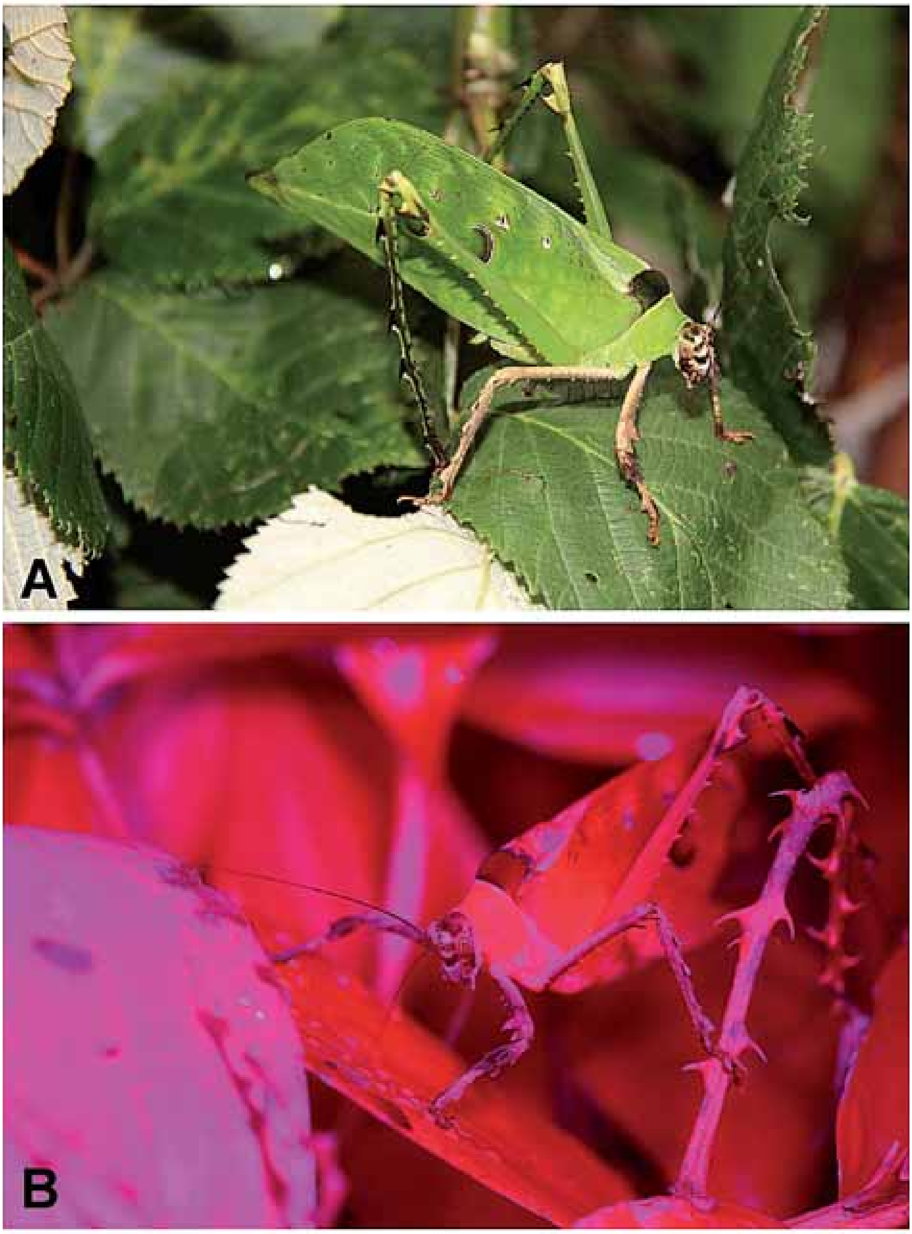


Fig. 8: The Malaysian katydid *Ancylecha fenestrata* (**A**) shows a strong NIR-reflectance (**B**).
Abb. 8: Die Malaysische Blattschrecke *Ancylecha fenestrata* (**A**) zeigt eine starke NIR-Reflexion (**B**).

a term still widely used by enthusiastic amateurs and professional infrared photographers. Since then infrared photography has been frequently used in different fields of science (e.g. CLARK 1947; GIBSON 1978; 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.

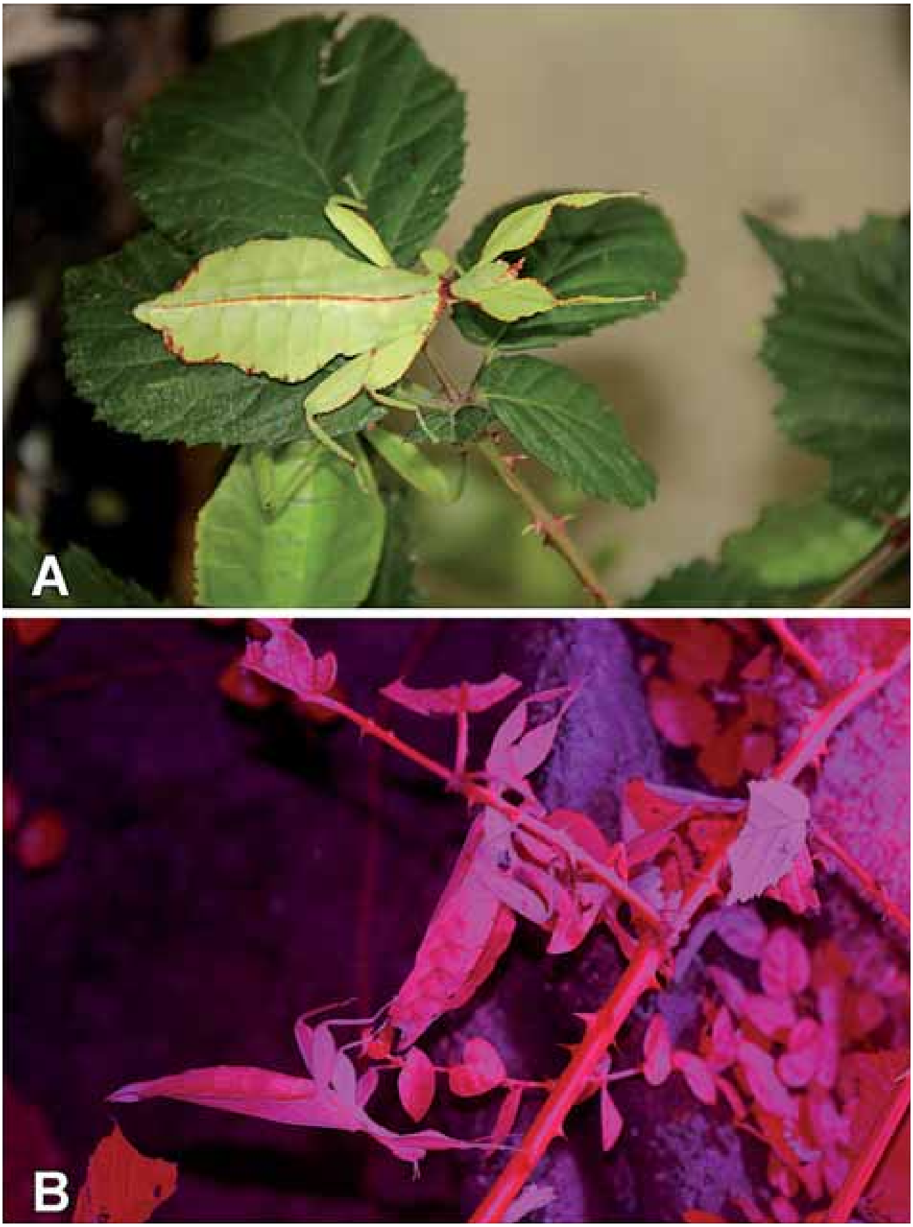


Fig. 10: The leaf insect *Phyllium celebicum* (**A**) and its NIR-reflectance (**B**) similarly strong as the surrounding vegetation.

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 (charge-coupled 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 NDVI-camera 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 auto-exposure 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 NIR-photography 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 Krempels (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 post-processing 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 NIR-reflectance 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 & McKenzie 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 IXα as prosthetic group (Przibram & Lederer 1933; Kawooya et al. 1985; Okay 1945; Passama-Vuillaume & Barbier 1966; Rüdiger 1970; Holden et al. 1987; Willig 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 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 NIR-reflectance 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, Wojtusiak 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 (Partridge 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 IR-reflectance 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 NIR-reflectance 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 metallic-coloured 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.

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Appendix

Tab. 1: NIR-reflectance of insects from museum collections as estimated by "Red-Edge"-Photography. Number of examined specimens in brackets after the scientific name.

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			
Chrysaspis aurovittata (Saunders, 1867) (2) West Africa	Buprestidae	Green metallic	No
Chrysaspis elongata (Olivier, 1790) (3) Sierra Leone	Buprestidae	Green metallic (red tint)	No
Chrysochroa andamanensis Saunders, 1867 (2) Southeast-Asia	Buprestidae	Green metallic	No
Chrysochroa buqueti (Gory, 1833) (1) Malysia, Borneo	Buprestidae	Black with big yellow markings on the elytra	No (black areas) and medium reflectance of the markings
Chrysochroa chrysura Gory, 1840 (2) Phillippines	Buprestidae	Green metallic	No
Chrysochroa edwardsi 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
Chrysochroa fulminans (Fabricius, 1787) (10) Malysia, Indonesia etc.	Buprestidae	Green metallic	No
Chrysochroa ignita (Linnaeus, 1758) (2) Malaysia, Indochina	Buprestidae	Green metallic	No
Chrysochroa saundersi Saunders, 1866 (3) 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
Chrysodema alberti Lander, 2000 (1) Asia	Buprestidae	Metallic green	No
Chrysodema aurofoveata Guérin, 1830 (5) Australia	Buprestidae	Metallic green	No
Chrysodema purpureiventris Deyrolle, 1864 (1) Thailand	Buprestidae	Metallic green	No
Chrysodema swierstrae Landsberg, 1833 (1) Indonesia, Sumatra, Malaysia	Buprestidae	Metallic dark green	No

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

Cyrioides imperialis (Fabricius, 1801) (5) Australia	Buprestidae	Black with numerous orange-brown striped markings	Only the orange markings on the elytra show a medium reflectance
Evides triangularis (Thomson, 1878) (2) Africa	Buprestidae	Metallic Green	No
Evides pubiventris (Laporte & Gory, 1835) (8) Africa	Buprestidae	Metallic Green	No
Iridotaenia sumptuosa (Laporte & Gory, 1835) (2) Indonesia, Sumatra	Buprestidae	Metallic green	No
Julodis rothii (Sturm, 1843) (1) Palestine	Buprestidae	Black elytra and pronotum with yellow markings	No (black elytra) and medium reflectance of the yellow markings of the elytra and pronotum
Julodis sulcicollis Laporte & Gory, 1835 (1) Africa	Buprestidae	Black elytra and pronotum with light markings	No (black elytra) and medium reflectance of the yellow markings of elytra and pronotum
Julodis variolaris bucharica (Semenov, 1893) (14) Turkmensitan	Buprestidae	Black elytra and pronotum with yellowt markings	No (black elytra) and medium reflectance Iof the yellow markings of elytra and pronotum
Julodis variolaris freygessneri Meyer-Darcis, 1883 (6) Turkmenistan	Buprestidae	Black elytra and pronotum with yellowt markings	No (black elytra) and medium reflectance Iof the yellow markings of elytra and pronotum
Lampestis fastuosa (Fabricius, 1775) (3) India	Buprestidae	Metallic green	No
Philocteanus maitlandi Lansberge, 1883 (2) Thailand	Buprestidae	Metallic green with reddish tint	No
Sterapsis brevicornis (Klug, 1835) (5) Senegal	Buprestidae	Metallic green ; pronotum red metallic tint	No
Steraspis colossa Harold, 1878 (1) Somalia	Buprestidae	Metallic green	No
Steraspis scabra ((Fabricius, 1775) (3) Senegal	Buprestidae	Metallic green	No
Steraspis squamosa (Klug, 1829) (5) Egypt, Nubia	Buprestidae	Metallic green	No
Sternocera aequisignata Saunders, 1866 (10) India, Thailand	Buprestidae	Metallic emerald iridescence	No (green elytra); some specimens with a very weak reflectance of the elytra or medium reflectance of markings on the pronotum
Sternocera castanea boucardi Saunders, 1874 (6) Tanzania, Kenya	Buprestidae	Dark elytra with big yellow markings	No (black elytra) and medium reflectance of the yellow markings of elytra and pronotum
Sternocera castanea irregularis (Latreille, 1835) (2) Sudan	Buprestidae	Redish elytra with small lighter marking; black pronotum with orange markings	Weak to medium (reddish elytra), no (pronotum), and strong (elytra) reflectance
Sternocera chrysis chrysioides Laporte & Gory, 1837 (3) India	Buprestidae	Reddish elytra	Weak to medium (reddish elytra), no (dark pronotum) reflectance beside those of the small specular reflections

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

Sternocera diardii Gory, 1840 (3)	Buprestidae	Metallic green to metallic gold and blue	No
Sternocera feldspathica White, 1843 (2) South Africa	Buprestidae	Orange to red (elytra)	Medium (reddish elytra)
Sternocera hildebrandti Harold, 1878 (6) Ethiopia, Kenya, Tanzania	Buprestidae	Reddish brown elytra; black pronotum	Weak to medium (reddish elytra) and no (black pronotum) reflectance
Sternocera hunteri Waterhouse, 1898 (1) Somalia, Kenya, Tanzania	Buprestidae	Reddish brown elytra; black pronotum	Weak to medium (reddish elytra) and no (black pronotum), reflectance
Sternocera laevigata (Olivier, 1790) (5)	Buprestidae	Dark	No (black elytra)
Sternocera sternicornis (Linnaeus, 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 irregularis Fabricius, 1792 (10) Europe	Carabidae	Black with metallic red and green shining	Very weak
Carabus scabrosus amasicus Csiki, 1927 (2)	Carabidae	Black	No
Carabus scabrosus audouini Brullé, 1837 (2)	Carabidae	Black with a very weak green metallic shining	No
Carabus scabrosus caucasicus Adams, 1817 (2)	Carabidae	Black with a very weak green metallic shining	No
Carabus scabrosus colchicus Motschulsky, 1844 (2)	Carabidae	Black with a very weak green metallic shining	No
Carabus scabrosus 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
Carabus scabrosus tauricus Bonell, 1810 (2) Crimia, Ukraine	Carabidae	Black with a very weak green metallic shining	No
Carabus scabrosus transversalis Csiki, 1927 (2)	Carabidae	Black	No
Carabus syriacus Kollar, 1843 (2) Israel	Carabidae	Black	No
Carabus (Procerus) gigas Creutzer, 1799 (4) Europa	Carabidae	Black	No
Carabus (Procrustes) anatolicus anatolicus Chaudoir, 1857 (2)	Carabidae	Black	No
Carabus (Procrustes) chevrolati Cristoforis & Jan, 1837 (2) Turkey, SW-Georgia	Carabidae	Black	No

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

Carabus (Procrustes) clypeatus Adams, 1817 (2)	Carabidae	Black	No
Carabus (Procrustes) coriaceus Linnaeus, 1758 (2) Europa	Carabidae	Black	No
Sternotomis bohemani (Chevrolat, 1844) (1) South Africa	Cerambycidae	Green metallic with orange markings on elytra and pronotum	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
Plaesiorrhina cincta Allard, 1991 (4) Africa	Cetoniidae	Dark metallic with orange stripe on the elytra	Weak reflectance and medium (orange stripe) reflectance
Bothynus cunctator (Mannerheim, 1829) (2) Neotropis	Dynastidae	Dark brown to black	Very weak
Oryctes boas (Fabricius, 1777) (3)	Dynastidae	Dark brown to black	Very weak
Alaus lacteus Candeze, 1857 (2) Philippines, Borneo etc.	Elateridae	Brownish elytra; pronotum with dark spots	No (dark spots) and medium reflectance of elytra and pronotum
Agrypnus fuscipes Fleutiaux, 1947 (2) South Asia	Elateridae	Brownish	Weak
Camposternus auratus (Drury, 1773) (2) China	Elateridae	Golden bown with greenish tint	No to very weak
Chalcolepidius zonatus Eschscholtz, 1829 (2) South America	Elateridae	Black elytra; pronotum with light yellow markings	No (black elytra) and high reflectance of the yellow markings of elytra and pronotum
Pyrophorus phosphorescens Laporte, 1840 (2) Trinidad, Tobago	Elateridae	Brown with two small bioluminescent spots on the pronotum	Medium (pronotum, elytra) and high (spots) reflectance
Semiotus distinctus Herbst, 1806 (3) Brazil, Paraguay, Argentina	Elateridae	Orange with brownish stripes	Weak (brown parts) and weak to medium (orange parts) reflectance
Semiotus imperialis (Guèrin-Menéille, 1844) (3) Peru, Colombia, Venezuela	Elateridae	Orange elytra and pronotum; black spots and a long, reddish stripe in the middle of the head, framed by two dark stripes	High reflectance only of the elytra,the pronotum and the , reddish stripe
Semiotus intermedius (Herbst, 1806) (3) Brazil	Elateridae	Orange with black stripes on the elytra; orange black markings on the pronotum	No (black parts) and medium to high (orange parts) of the body reflectance
Tetralobus flabellicornis (Linnaeus, 1758) (2) South Africa	Elateridae	Black with yellowish markings on the elytra and pronotum	Weak to medium reflectance of the yellowish markings
Geotrupes pyrennaeus (Charpentier, 1825) (9) Europe	Geotrupidae	Black	No

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

Geotrupes vernalis (Linnaeus, 1758) (10) Europe, Asia Minor	Geotrupidae	Black	No
Atholus duodecimstriatus (Schrank, 1781) (4) Europe	Histeridae	Black	No
Lamprima adolphinae (Gestro, 1875) (1) Indonesia, New Guinea	Lucanidae	Very dark, metallic green	No
Anomala gemmula Arrow, 1912 (2) South India	Scarabaeidae	Brown abdomen with black head	Weak (abdomen) ??????
Anoplognathus parvalus (Donovan, 1805) (1) Australia	Scarabaeidae	Metallic	Weak
Anoplognathus viridiaeneus Waterhouse, 1873 (1) Australia	Scarabaeidae	Metallic green to metallic brown	Weak to medium
Caelorrhina superba Gerstäcker, 1883 (5) Tanzania	Scarabaeidae	Metallic green; olive	Some specimens show no or a very weak reflectance, others a medium reflectance of elytra and pronoum
Cheirolasia burkei Westwood, 1843 (1) South Africa	Scarabaeidae	Black with yellow point markings on the elytra; yellow markings on the pronotum	Medium to high reflectance only of the yellow markings
Chelorrhina savagei (Harris, 1844) (1) Zaire, Congo	Scarabaeidae	Black with numerous yellow stripes and markings	Medium reflectance only of the yellow markings
Chondrorrhina picturata (Harold, 1878) (1) Central Africa	Scarabaeidae	Dark reddish -brown with large orange stripes at the side. Inside the stripes black points	Weak to medium reflectance except the black stripes and points
Chrysina macropus Francillon, 1795 (1) Mexico	Scarabaeidae	Light green	No
Dicranocephalus bowringi Pascoe, 1863 (3) China	Scarabaeidae	Light brown	Weak to medium refelctance of the elytra. The pronotum appeared somehow darker.
Diplognatha gagates Forster, 1771 (1) Africa	Scarabaeidae	Red brown	Very weak reflectance of the elytra. Nearly no reflectance of the pronotum.
Eudicella smithi (MacLeay, 1838) (1) Central-, West-, and East Africa	Scarabaeidae	Orange elytra with black point markings; pronotum olive metallic green with red tint. Legs red brown	No (point markings), medium (elytra, legs) a nd weak to medium (pronotum) reflectance.
Pachnoda inscripta (Gory & Percheron, 1833) (1) Africa	Scarabaeidae	Black markings on yellow ground	Only the yellow parts of the elytra show a medium reflectance
Gnathocera bilineata Kraatz, 1886 (1) tropical Africa	Scarabaeidae	Light brown elytra with dark stripes	Only the light brown areshow a medium reflectance
Heliocopris gigas Linnaeus, 1758 (1) Africa	Scarabaeidae	Very dark to black	No

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

Heterorrhina elegans (Fabricius, 1781) (1) South India	Scarabaeidae	Emerald metallic green	Nearly no reflectance
Heterorrhina obesa Janson, 1884 (3) India	Scarabaeidae	Dark green	Very weak reflectance of the elytra.
Ischiosopha lucivorax Kraatz, 1890 (13) Australian region	Scarabaeidae	Green	Nearly no reflectance
Mecynorrhina torquata (Drury, 1782) (1) West Africa	Scarabaeidae	Green to brown	Nearly no reflectance
Micropoecila cincta (Gory & Percheron, 1833) (1) Australia	Scarabaeidae	Brown with black markings and black legs	Generally weak, but weak to medium (lighter markings at the side) reflectance.
Oxysternum conspicillatum (Weber, 1801) (2) Ecuador	Scarabaeidae	Dark green	No
Pachnoda poggei (Harold, 1878) (3) Africa	Scarabaeidae	Black with large orange markings on the elytra	No (black elytra) and mediumreflectance of the orange markings
Pachnoda savignyi (Gory & Percheron , 1833) (1) Africa	Scarabaeidae	Dark-brown with orange markings on the elytra and pronotum	Very weak reflectance of the dark body part and medium to high reflectance of the the orange markings
Pachnoda sinuata Harold, 1878 (2) Africa	Scarabaeidae	Black with yellow markings	No (black parts) and medium (yellow parts) reflectance
Pelidnota cyanitarsis Gory, 1833 (1) Southern America	Scarabaeidae	Dark metallic green	No to very weak reflectance
Pelidnota sumptuosa Vigors, 1825 (1) Southern America	Scarabaeidae	Metallic green (red tint)	No
Phaedimus inermis Moser, 1926 (1) Southern America	Scarabaeidae	Yellow green metallic	Medium
Phanaeus (Sulcophanaeus) auricollis (Harold, 1880) (1) Columbia, Venezuela	Scarabaeidae	Dark green	No
Phanaeus (Sulcophaeneus) imperator Chevrolat, 1844 (1), Bolivia, Paraguay	Scarabaeidae	Black with reddish stripe and greenish iridiscence at the end of the abdomen	No (body) and weak (reddish stripe, greenish iridiscence) reflectance
Plusiotis batesi Boucard, 1875 (1) Central America	Scarabaeidae	Golden with greenish tint	Weak metallic
Plusiotis (Chrysina) gloriosa (LeConte, 1854) (1) USA	Scarabaeidae	Vividly green	Weak metallic
Plusiotis (Chrysina) resplendens (Boucard, 1875) (1) Costa Rica, Panama	Scarabaeidae	Light metallic green	Weak metallic
Ptychodesthes gratiosa (Ancey, 1881) (6) Tanzania	Scarabaeidae	Green with orange tint	Very weak

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

Rutela laeta Weber, 1801 (1) Central-America	Scarabaeidae	Metallic green elytra; orange color markings at the caput	The green elytra show only a Weak reflectance (elytra) and weak to medium (orange color markings) reflectance
Smaragdesthes africana (Drury, 1773) (6) Africa	Scarabaeidae	Emerald green	Medium NIR reflectance
Stephanorrhina guttata Olivier, 1789 (8) Southeast Africa	Scarabaeidae	Emerald elytra and pronotum; elytr with additional orange markings and white points	No (elytra), weak (orange markings) and high (white points) reflectance
Trigonophorus delesserti (Guérin-Méneville, 1839) (2) India	Scarabaeidae	Green to brown	Not to very weak
Hemiptera (Heteroptera)			
Dolycoris baccarum (Linnaeus, 1758) (32) Europe to Asia	Pentatomidae	Brown	No to very weak; reddish parts with weak reflectance
Dolycoris penicillatus Horvath, 1903 (2) Europe	Pentatomidae	Light brown	Weak
Holcogaster fibulata (Germar, 1831) (16) Europe	Pentatomidae	Light brown with black markings	Weak to medium; black stripes no reflectance
Holcogaster exilis Horvath, 1903 (1) Europe	Pentatomidae	Light brown with black markings	Weak to medium; black stripes no reflectance
Chlorochroa juniperina (22) Europe	Pentatomidae	Green	Weak (a few specimens medium)
Chlorochroa pinicola (Mulsant & Rey, 1852) (18) Europe	Pentatomidae	Olive green	Weak
Palomena prasina (Linnaeus, 1761) (18) Europe	Pentatomidae	Green with black stripes	Weak to medium; black stripes no reflectance
Palomena viridissima (Linnaeus, 1761) (30) Europe	Pentatomidae	Green with black markings	Medium; black markings no)
Nezara viridula (Linnaeus, 1758) (24) cosmopolit	Pentatomidae	Green	High
Stenozygum coloratum (Klug, 1845) (1) Europe	Pentatomidae	Black with red and yellow markings	Medium (red and yellow markings) and no (black areas) reflectance
Trochiscocoris rotundatus Horvath, 1895 (1) Palaearctic Region	Pentatomidae	Black, with very fine yellow markings	Medium (yellow markings) and no (black areas) reflectance
Hymenoptera			
Pepsis sp. (2) USA	Pompilidae	Black with reddish wings	No (black areas) and relatively high (wings) reflectance; wings totally opaque to the blue part of the spectrum
Chlorion aerarium Patton, 1879 (1) USA	Sphecidae	Metallic black green with dark wings	No (black areas) and relatively high (wings) reflectance; wings totally opaque to the blue part of the spectrum

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

Polistes biglumis (Linnaeus, 1758) (5) North-Africa, South- and Middle-Europe	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Polistes nimpha (Christ, 1791) (1) South and Middle Europe	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Vespa (Dolichovespula) adulterina (du Buysson, 1905) (3) Europe, Japan, North America	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Vespa crabro Linnaeus, 1758 (1) Europe	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Vespa (Vespula) germanica (Fabricius, 1793) (10) Europe, Asia, Africa	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Vespa orientalis Linnaeus, 1771 (1) South Europe	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Vespa rufa (Linnaeus, 1758) (10) Holarctis	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Vespa (Dolichovespula) saxonica Fabricius, 1793 (2) Middle Europe	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Vespa (Dolichovespula) sylvestris (Scopoli, 1763) (4) Europe, Central Asia etc.	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Vespa vulgaris (Linnaeus, 1758) (23) Eurasia	Vespidae	Yellow / black	No (black parts) and medium (yellow parts, wings) reflectance
Lepidoptera			
Endromis versiocolora (Linnaeus, 1758) (caterpillar) (1) Palearctis	Endromidae	Green	Medium
Saturnia pavonia (Linnaeus, 1758) (caterpillar) (1) Europe	Saturniidae	Green with black stripes	Medium; stripes no
Ennomos alniaria (Linnaeus, 1758) (4) Europe	Geometridae	Light yellow brown	Medium
Ennomos erosia (Denis & Schiffermüller, 1775) (4) Europe	Geometridae	Light yellow brown	Medium
Cymothoe coccinata (Hewitson, 1874) (3) Central Africa	Nymphalidae	Orange	Medium to High
Prepona chromus (Gérin-Ménéville, 1844) (1) South America	Nymphalidae	Dark brown with light blue spots	Weak to medium (wings); spotks slightly stronger
Papilio euchenor 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
Papilio paris Linnaeus, 1758 (1) South Asia	Papilionidae	Very dark metallic green to black wings with light blue markings	Generelly very weak NIR reflectance, weak to medium NIR reflectance in blue spots

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

Teinopalpus 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 iridiscent areas), weak to medium(orange markings) and strong (yellow areas) reflectance
Troides priamus (Male) (Linnaeus, 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 spots and abdomen) reflectance
Mantodea			
Acanthops falcataria Goeze, 1778 (3) South America	Mantidae	Dark brown	Weak
Choeradodis rhombicollis (Latreille, 1833) (3) South America	Mantidae	Green / Yellow	Medium to high
Deroplatys desiccata Beier, 1935 (2) Borneo, Indonesien, Malaysia	Mantidae	Dark brown	Weak
Deroplatys sicciofolium (Saussure, 1870) (2) Asia	Mantidae	Deep dark brown	Very weak to weak. Lighter specimens weak to medium
Deroplatys truncata (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
Deroplatys trigonodera (Westwood, 1889) (2) Asia	Mantidae	Whitish brown to brown	Medium (like leaf litter; in a darker specimen slightly reduced
Orthodera ministralis (Fabricius, 1775) (3) Australia	Mantidae	Green (light brown); colours were clearly faded	Medium
Stagmatoptera precaria (Linnaeus , 1758) (3) Southern America	Mantidae)	Faded light yellow green to light brown	Medium (body, forewings, yellow markings on the rear wings), body somwhat lower
Tropidomantis tenera Stal, 1860 (5) Thailand, Malaysia, Borneo etc.	Mantidae	Whitish transparent	very high
Odonata			
Calopteryx splendens (Harris, 1782) (1) palearctic distribution	Calopterygidae	Metallic dark blue; green coloration	No
Libellula depressa (female) (Linnaeus, 1758) (1) Europe	Libellulidae	Brown abdomen with yellow patches	Weak (dark brown body parts), weak to medium (light brown parts) and medium reflectance (yellow spots)
Libellula quadrimaculata (male) (Linnaeus, 1758) (1) Holarctis	Libellulidae	Brownish abdomen	Very weak
Orthethrum cancellatum (male) (Linnaeus, 1758) (1) palearctic distibution	Libellulidae	Blueish abdomen	Weak

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

Orthoptera			
Conocephalus longipes (Redtenbacher, 1891) (4) Southern America	Tettigoniidae	Greenish and yellow brown specimens	Medium
Euconocephalus brachyxiphus (Redtenbacher, 1891) (4) China	Tettigoniidae	Green/Yellow-brown	Medium
Euconocephalus gracilis (Redtenbacher, 1891) (8) Southeast Asia	Tettigoniidae	Greenish and yellow brown specimens	Medium
Euconocephalus indicus (Redtenbacher, 1891) (4) India	Tettigoniidae	Yellow and green specimens	Medium
Neoconocephalus brunneri (Redtenbacher, 1891) (4) Southern America	Tettigoniidae	Green/Yellow	Medium to High
Neoconocephalus occidentalis (Saussare, 1859) (4) Central America	Tettigoniidae	Yellow/brown	Weak
Neoconocephalus precinus (Redtenbacher, 1891) (8) Southern America (Brazil)	Tettigoniidae	Medium brown	Weak to medium
Neoconocephalus punctipes (Redtenbacher, 1891) (4) Central America	Tettigoniidae	Yellow	Weak to Medium
Neoconocephalus triops (Linnaeus, 1758) (1) North and Central America	Tettigoniidae	Darker yellow/brown	Medium
Neoconocephalus viridis (Redtenbacher, 1891) (4) South America	Tettigoniidae	Green to yellow/brown	Medium
Ruspolia differens (Serville, 1838) (2) Africa	Tettigoniidae	Medium brown	Weak
Phaneroptera falcata (Poda, 1761) (31) Middle Europe	Phaneropteridae	Green and light brown specimens	Medium to high also the green forewings
Phaneroptera nana (Fieber, 1853) (26) North Africa, Benelux	Phaneropteridae	Green and light brown specimens	Medium to high
Phasmatodea			
Eurycnema versirubra (Serville, 1838) (2) Southeast-Asia	Phasmatodea	Big green specimens and smaller brownish specimens	Medium to high (green forewings of the big specimens), weak to medium (smaller specimens)

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.

Species	Family	Order	Color	NIR-reflectance
Lepidoptera				
Attacus atlas (Linnaeus, 1758) (caterpillar), Southeast Asia	Saturniidae	Lepidoptera	Green with whitish cover	High to very high
Mantodea				
Gongylus gongylodes (Linnaeus, 1758) Southeast-Asia (India, Java, Sri Lanka, Thailand)	Empusidae	Mantodea	Light to dark brown	Weak (comparable to leaves)
Mantis religiosa (Linnaeus, 1758) Europe	Mantidae	Mantodea	Green	High
Sphodromantis viridis (Forsskal, 1775) ? Africa	Mantidae	Mantodea	Green	High
Orthoptera				
Ancylecha fenestrata (Fabricius, 1793) (adult) Malaysia	Tettigoniidae	Orthoptera	Green with dark markings	Very high
Ancylecha fenestrata (Fabricius, 1793) (juvenile nymphs) Malaysia	Tettigoniidae	Orthoptera	Green with dark markings	Very high
Stilpnochlora couloniana (Saussure, 1861) (adult) Middle America, Florida	Tettigoniidae	Orthoptera	Green	Very high
Stilpnochlora couloniana (Saussure, 1861) (nymph) Middle America, Florida	Tettigoniidae	Orthoptera	Green	Very high
Schistocerca gregaria Forsskal, 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 (!)
Schistocerca gregaria Forsskal, 1775 (juvenile nymphs) Africa, Middle East, Asia	Acrididae	Orthoptera	Yellow/green with big black markings	High to very high ; no dark patterns
Schistocerca gregaria Forsskal, 1775 (young nymphs) Africa, Middle East, Asia	Acrididae	Orthoptera	Black with yellow eyes	Nearly no (nymphs) reflectance
Tropidacris collaris (Stoll, 1813) South-America	Romaleidae	Orthoptera	Green with reddish tint and light brown wings	High
Phasmatodea				
Heteropteryx dilatata (Parkinson, 1798) Malaysia, Thailand	Heteropterygidae	Phasmatodea	Green	Very high near infrared reflectance
Diapherodes gigantea (female) (Gmelin 1789) Middle America	Phasmatidae	Phasmatodea	Green	Very high
Extatosoma tiaratum (MacLeay, 1827) Australia	Phasmatidae	Phasmatodea	Green to brown	Medium to high
Lonchodes bosei herberti Günther, 1930 Southeast-Asia	Phasmatidae	Phasmatodea	Brownish-green	Medium (comparable to twigs)
Megacrania batesii (Kirby, 1896) Australia, New-Guinea, Solomon Islands, Phillipines etc.	Phasmatidae	Phasmatodea	Brown with bluish-green legs	Weak, the blue-green legs show a medium to high reflectance
Medauroidea extradentata (Brunner von Watteneyl, 1907) Vietnam	Phasmatidae	Phasmatodea	Brown	Weak to medium near (comparable to twigs)
Phyllium celebicum de Haan, 1842 Sulawesi, Ambon	Phyllidae	Phasmatodea	Green / yellow	Very high
Peruphasma schultei Conle & Hennemann, 2005 Peru	Pseudophasmatidae	Phasmatodea	Black with yellow eyes	Very low (body; overall reflectance including the spectral range of NIR) and strong (eyes, wings) reflectance

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