Thermal canopy photography in forestry - an alternative to optical cover photography

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Hemispherical canopy photography is a widely used technique to observe crown-related forest variables. However, standardization of this technique remains challenging, as exposure and threshold settings continue to constitute the main sources of variation of such photographs. This paper presents a new method to overcome standardization issues by using thermal canopy photography. Using a thermal camera, images are produced which are not critically limited in their dynamic range so that photographic exposure becomes irrelevant. Moreover, the high temperature contrast between "sky" and "non-sky", resulting from extreme low sky temperatures, facilitates the unambiguous selection of a threshold which separates "sky" from "non-sky" pixels. For a comparison, we have taken canopy images with a high-resolution thermal camera (VarioCam hr head - Infratec, Dresden, Germany) and an optical camera (Nikon D70s). The correlation of canopy closure values derived from the image pairs was *r* = 0.98. Our findings thus show that thermal canopy photography is a promising and simple to use alternative to optical canopy photography, because it limits possible sources of variability, since exposure settings and threshold definition cease to be an issue.

Keywords: Hemispherical Photographs, Exposure, Thresholding, Thermal Images, Canopy Structure

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Introduction

Information on gap fraction, leaf area, and other structural variables of forest canopies are required parameters in a wide range of studies, but their "measurement" is evidently difficult. Cover photography (Macfarlane et al. 2007a, 2007b) and hemispherical photography in particular are terrestrial remote-sensing techniques widely employed to produce upward facing images of sections of the forest canopy (Hale & Edwards 2002). The term "hemispherical" here refers to the approach of taking wide-angle photographs. These photographs, frequently taken with a fisheye lens, form the basis for subsequent analyses with gap fraction (or its complement canopy closure) being the most frequently derived target variable (Jonckheere et al. 2005). Moreover, canopy related attributes like, *e.g.*, near-ground solar radiation (Zou et al. 2007), leaf area index (Zhang et al. 2005), and microclimate below canopy (Van Pelt & Franklin 2000) are modeled from hemispherical photographs.

Yet before they may be analyzed, raw photographs need to be pre-processed, *i.e.*, converted into binary images comprising just "sky" and "non-sky" pixels. Here, a crucial step is the selection of a radiometric threshold value that correctly separates "sky" from "non-sky" in the photograph, a process referred to as "thresholding". Thresholding has been identified as a source of inconsistencies by several studies that aim at identifying an "optimal threshold" either through automatic (Nobis & Hunziker 2005, Macfarlane 2011) or manual approaches (Frazer et al. 2001). When preparing a threshold, it is important to take the canopy photographs with a photographic exposure setting that allows for a clear separation of the classes "sky" and "non-sky" (Rich 1990). However, the definition of a standardized optimal exposure is challenging because various conditions, including cloudiness and illumination geometry may interfere. The effects of photographic exposure on optical hemispherical photography can be immense and have been discussed intensively (Chen et al. 1991, Wagner 1994, 1998, Macfarlane et al. 2000, Zhang et al. 2005, Beckschäfer et al. 2013). For neither of the processing steps - exposure and threshold definition - standard protocols do yet exist which are consistently applied throughout the scientific community. As a consequence, comparability between and within studies is hampered. Furthermore, gamma correction is another critical preprocessing step (Chianucci & Cutini 2012) that can affect estimates based on hemispherical photography (Leblanc et al. 2005) and mainly influences the lighter midtones of an optical photograph which are linked to canopy transmittance.

While hemispherical and cover photography of forest canopy has been implemented and researched most frequently by using optical cameras that work in the visible spectral domain, we suggest a novel approach using a thermal camera which records the emission of radiation instead of a blend of direct, scattered, reflected, and transmitted radiation in the visible range of the spectrum. We hypothesize that recent technological advances in thermal photography might allow to overcome the challenges mentioned in standardizing terrestrial forest canopy photographs.

All objects that have a temperature above absolute zero (-273°C) emit radiation in the wavelength range of 7-14 µm (thermal infrared). Thermal cameras are sensitive in this spectral range, record thermal infrared radiation, and translate it into temperature values. Thermal images may be employed for research into any temperature-related features including plant physiological processes like stomatal conductance (Matsumoto et al. 2005) or the comparison of crown temperatures between urban tree species (Leuzinger et al. 2010). Contrary to the thermal radiation emitted by plant tissue which is close to the ambient air temperature, there is only a small amount of thermal radiation emitted by the upper atmosphere. A thermal camera pointed to clear sky will measure a temperature of around -30 °C independent from the ambient air temperature. This large difference in temperature between the sky as background and the tree canopy in the foreground promises to be an excellent basis to unambiguously distinguish "sky" pixels from "non-sky" pixels in a terrestrial canopy photograph taken with a thermal camera. Under cloudy conditions the temperature difference will decrease because the amount of emitted radiation from low-lying clouds is higher but the measured cloud temperature is below zero degree nevertheless.

Moreover, the dynamic range of a thermal camera is large: it covers a range from -40 to 120 °C and is thus considerably larger than that occurring in a forest canopy thermal photograph. In contrast, optical cameras have a limited dynamic range (in the order of magnitude of 6 to 8 f-stops), which frequently causes an over-exposure of vegetation parts due to inadequate exposure settings (Wagner 1998, Zhang et al. 2005, Beckschäfer et al. 2013).

In this study we compare canopy closure estimates obtained from canopy photographs taken with an optical camera with those derived from images taken with a thermal camera. We introduce thermal photography as a possibility for the standardization of terrestrial forest canopy photography.

Materials and methods

Study site

Canopy photographs were taken at 12 locations within the Forest Botanical Garden at Göttingen University (WGS84: 51° 3′ 28.08″ N, 9° 57′ 44.28″ E). Optical and thermal photographs were taken at the same locations immediately one after another. The selection of the 12 locations was such that a range of canopy openness situations was covered as we expect it to be typical in deciduous forests. As we were focusing on pure methodological differences, we did not apply a probabilistic sampling scheme as it would be recommended for, *e.g.*, assessing light conditions in a forest (Leblanc et al. 2005, Macfarlane et al. 2007b).

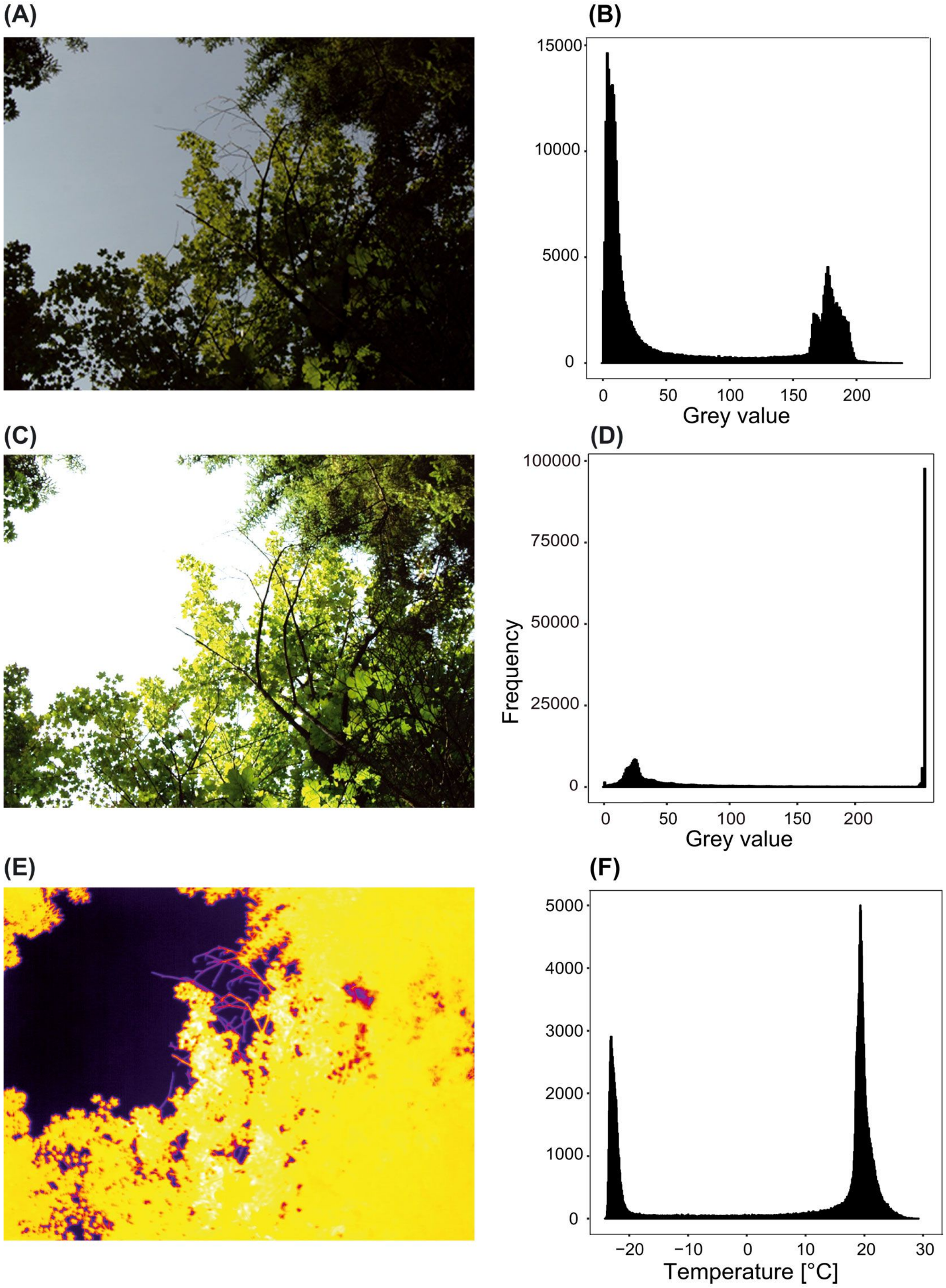

Fig. 1 - (A) Optical photograph (histogram-exposed, aperture F8.0, shutter speed 1/250) and (B) its grey value histogram. (C) Autoexposed optical photograph and (D) its grey value histogram. (E) Thermal image taken at the same location as (A) and (B), where black indicates sky and yellow represents vegetation; and (F) the corresponding temperature value histogram. The two peaks indicate sky and vegetation pixels. The peaks are best pronounced in the thermal image.

Estimation of canopy attributes from thermal photography

Thermal images were taken with a VarioCAM hr head 720 (Infratec, Dresden, Germany) that has a resolution of 640x480 pixels and a spectral range of 7.5-14 µm. The camera was equipped with a 30 mm lens with a field-of-view of 30° x 23° and was mounted on a tripod at 1.3 m height. It was orientated to magnetic north using a compass and leveled to exactly face the vertical using a bubble-level. Images were stored in a raw format with a dynamic range of 16 bit in a temperature range between -40 to +120 °C. Photographs were taken between 8 and 10 a.m. on 26/07/2013 where the day temperatures ranged between 18 and 23 °C. We assumed a constant emissivity of 0.98 as an average for forest vegetation (Rubio et al. 1997).

For data processing the software packages Irbis 3 Plus (InfraTec, Dresden, Germany) and "R" (R Core Team 2013) with the EBImage package (Sklyar et al. 2007) were used. We converted each thermal raw image into an ASCII-file of temperature values per pixel. To separate "sky" and "non-sky" pixels we applied a global threshold of 0 °C. Each pixel below 0 °C was classified as "sky", while pixels above 0 °C were classified as "non-sky". Canopy closure estimates, computed as unweighed gap fraction (Englund et al. 2000), were derived by counting the "non-sky" pixels per image.

Estimation of canopy attributes from optical photography

A NIKON D70s single lens reflex camera equipped with a standard 17-35 mm 1:2.8-4 lens (Tamron SP AF Aspherical DI LD - IF) was used for the acquisition of optical photographs. For the comparison of the field-of-view, we took one photograph with a 180° fisheye lens (Sigma AF 2.8/4.5 DC). Like the thermal camera, the optical camera was mounted on a tripod at 1.3 m height and leveled to face exactly the vertical using a bubble-level. The top of the camera (position of the flash socket) was orientated to the magnetic north using a compass (Beaudet & Messier 2002). The photographs were taken without direct sunlight entering the lens (Rich 1989) in the early morning. The basic camera settings mode "P" (Programmed Auto), ISO = 200, and matrix metering were used; the focal length was fixed to 17 mm. At each location a photograph was taken following the protocol for histogram exposure (Beckschäfer et al. 2013). Further, an auto-exposed photograph was taken.

Each photograph was manually aligned with the slightly smaller thermal images and cropped to the same extent using Adobe Photoshop® (Adobe Systems Corporation, San Jose, CA, USA). The section of the photograph covering the same scene as the thermal image was resampled to the resolution of the thermal camera. To the blue color plane of the 8-bit photograph an automated global thresholding was applied to avoid variations in the threshold setting caused by the manual interpretation of the photographs (Jonckheere et al. 2004). Following Beckschäfer et al. (2014), the "minimum thresholding algorithm" (Prewitt & Medelsohn 1966) implemented in ImageJ (Schneider et al. 2012) was used.

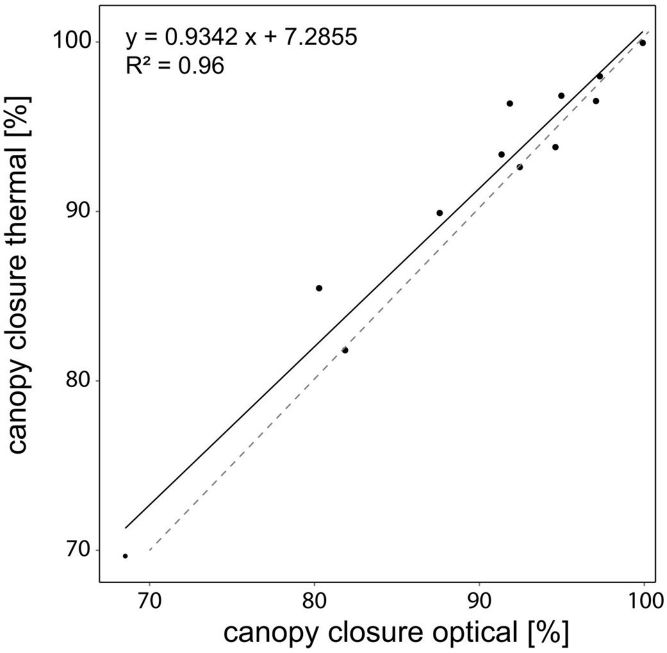

Fig. 2 - Canopy closure values based on optical photographs against canopy closure estimates based on thermal images. The dashed line is the 1:1 line and the solid line is the linear regression.

Results

Due to the narrow field-of-view of the thermal camera only a small part of the canopy is depicted in the photograph if compared to the area covered in a photograph taken with a 180° fisheye lens.

Thermal images (Fig. 1e and Fig. 1f) taken in the forest cover a wide range of temperature values from cold sky (-30 °C) to warm vegetation (+20 °C). In the temperature histogram (Fig. 1f), two distinct peaks can be clearly identified. The peak occurring at -23 °C represents "sky" pixels, with the majority of sky pixels showing a temperature in the range of -25 to -18 °C; this variation, of course, is also due to the composition of the atmosphere. The second peak at +20 °C represents "non-sky", *i.e.*, vegetation pixels with temperature values ranging from 15 to 28 °C. Between the two peaks the frequency values are very low. These intermediate temperature values are caused by mixed pixels covering vegetation and sky.

A visual comparison of Fig. 1a, Fig. 1c, and Fig. 1e shows that the thermal camera also clearly depicts small features like branches or individual leaves in the image. Thus, the thermal image allows a very clear distinction between sky and vegetation and no over-exposure occurs. In comparison, the auto-exposed image taken with the optical camera (Fig. 1c) shows a considerable loss of information due to overexposure: the corresponding histogram shows that half of the pixels are white (Fig. 1d).

Canopy closure values for the same image sections of thermal photography and optical photography showed a relatively strong relation (R^2 = 0.96 - Fig. 2); the mean absolute difference was 1.6 % and the regression line did not significantly deviate from the 1:1 line. Additionally, the slope indicated that the canopy closure of the thermal image increased by 0.9342 if the optical canopy closure increased by 1.

Discussion and Conclusion

Our study clearly demonstrates the potential of terrestrial thermal canopy photography to overcome the challenges of standardization in conventional optical canopy photography, while resulting in the same canopy closure observations. The major advantage of thermal canopy photography is that a standardized protocol can be formulated easily, because no exposure setting or gamma correction is needed and the process of determining a threshold is straightforward and insensitive to thresholding algorithm issues. In thermal photographs, a threshold to separate "sky" from "non-sky" pixels may be unambiguously defined due to the high contrast between sky and vegetation pixels in the temperature histogram. This facilitates the retrieval of reproducible results and increases the comparability of results among studies.

Extreme temperature contrasts occur during dry weather with clear sky (or low cloud cover). Although this is the ideal weather condition for image acquisition, nearly all weather conditions excluding rain will potentially allow for equally suitable images.

Thermal camera systems use uncooled microbolometer focal plane arrays (FPA) with a limited resolution of 640 x 480 pixels (0.3 megapixel) detecting the long wave radiation emitted by an object. Currently such thermal camera systems are referred to as high-resolution. Nevertheless, compared to the resolution of optical cameras (12-24 megapixel) their resolution is quite low. Thermal camera systems are not sensitive to visible light where the sun radiates the most energy and are therefore not affected by short-term variability in direct and diffuse solar radiation. Hence, cutting off the wavelengths lower than 8000 nm decreases the energy of the sun that reaches the detector and finally results in very low temperature values for the "sky" pixels. It is this physical principle that constitutes a strong advantage as images can be taken at any time of the day, compared to optical photographs which need to be taken during early morning or late evening hours. Changing sky conditions can represent challenging issues for optical cover photography (*i.e.*, shifting from clear sky to patchy cloud sky conditions). The application of thermal cameras may ultimately overcome the problem of changing sky conditions, and therefore, greatly increase the flexibility of work organization.

Optical cameras, in contrast, use high-resolution APS-C sensors (3008 x 2000 pixels) which are sensitive to the full visible spectrum of light, but as the dynamic range of such a sensor is smaller than the dynamic range of the scene to be photographed, overexposure, associated with a loss of information, frequently occurs in optical photographs.

Currently, a disadvantage of thermal photography is that only narrow field-of-view lenses are available for thermal cameras; full hemispherical or fisheye lenses are not yet on the market. Therefore, to date, an ideally suitable application for thermal cameras is cover photography as introduced by Macfarlane et al. (2007a, 2007b) which is a single view-angle method using a narrow field-of-view lens. This method has advantages over hemispherical photography (Pekin & Macfarlane 2009), *e.g.*, more accurate gap retrieval (Ryu et al. 2010, Chianucci & Cutini 2013), and is much closer to the thermal photography approach. To obtain nearly the same canopy image compared to a standard 35 mm lens for digital single lens reflex cameras, we recommend using a high-resolution thermal camera with a wide-angle 12.5 mm lens and field-of-view of 65° x 51°. An obstacle for the use of thermal camera systems in forest research might be the much higher price of the equipment (US$ 25000) compared to a standard optical DSLR cameras (US$ 1000). Nonetheless, our results and theoretical considerations suggest that thermal cameras equipped with hemispherical lenses may well overcome the critical standardization issues which currently constitute a challenge in optical terrestrial canopy photography.

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