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Originalarbeit

Nils Hoffmann[1], Thomas Schröder[1], Friedrich Schlüter[2], Peter Meinlschmidt[2]

Potential of infrared thermography to detect insect stages and defects in young trees

Potenzial von Infrarotthermographie zur Detektion von Insektenstadien und -schäden in Jungbäumen

Abstract

Living stages of the quarantine pest *Anoplophora chinensis* Forster, the so called Citrus Longhorned Beetle (CLB), have been detected repeatedly during import inspections of young trees in several European Union member states. CLB infested plants show almost no external symptoms for identification by visual inspection. Therefore, according to the European Union plant health legislation (EU-Commission-Implementing Decision 2012/138/EG), destructive sampling of the plants at random is required. Infrared thermography has been assessed as alternative, non-destructive testing method. Due to the quarantine status of CLB, the native goat moth, *Cossus cossus* L., was used as surrogate for the studies. Three types of thermography cameras have been tested using standardized wooden samples during two long-term measurements. Neither passive nor active thermographic methods were able to visualize enough differences in temperatures to detect larvae, boreholes or boredust inside of wooden samples. Therefore infrared thermography with its currently available technology seems to be no appropriate technique for detecting insect stages or defects in young trees.

Key words: Infrared thermography, non-destructive testing, *Anoplophora chinensis*, wood boring insect

Zusammenfassung

In den vergangenen Jahren wurden in den EU-Mitgliedstaaten lebende Stadien des Citrusbockkäfers (CLB), *Anoplophora chinensis*, im Rahmen der Importkontrolle an Jungbäumen festgestellt. Die in dem Durchführungsbeschluss 2012/138/EG festgelegten Einfuhrvorschriften der Europäischen Union fordern derzeit eine zerstörende Prüfung einer bestimmten Anzahl der Pflanzen. Hintergrund ist, dass trotz Befall mit dem CLB äußerlich keine Symptome vorhanden sind, die bei einer reinen visuellen Inspektion festgestellt werden können. Im Rahmen des EUPHRESCO-Projektes ANOPLORISK wurde in der vorliegenden Untersuchung aus einer Reihe von zerstörungsfreien Prüfverfahren die Infrarotthermographie als zerstörungsfreies Prüfverfahren angewandt. Aus Quarantänegründen wurde mit heimischen Weidenbohrerlarven, *Cossus cossus* L. (Modellorganismen), die den CLB-Larven in Größe und Fraßbild ähneln, gearbeitet. Mittels standardisierter Prüfkörper und präparierter Bohrlöcher wurden drei Thermographiekamera-Typen untersucht. Weder passive noch aktive Thermographieverfahren konnten ausreichende Temperaturkontraste darstellen, um Larven, Bohrlöcher oder Bohrspäne innerhalb des Holzes zu identifizieren. Infrarotthermographie scheint kein geeignetes Verfahren zur Aufspürung von Insektenstadien und -schäden in Jungbäumen zu sein.

Institute
Julius Kühn-Institut (JKI) – Federal Research Centre for Cultivated Plants, Institute for National and International Plant Health, Braunschweig, Germany[1]
Technology for Wood-based Materials, Fraunhofer Institute for Wood Research, Wilhelm-Klauditz-Institut, Braunschweig, Germany[2]

Correspondence
Dr. Thomas Schröder, Julius Kühn-Institut, Federal Research Centre for Cultivated Plants, Institute for National and International Plant Health, Messeweg 11–12, 38104 Braunschweig, Germany, E-Mail: thomas.schröder@jki.bund.de

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Stichwörter: Infrarotthermographie, zerstörungsfreie Prüfverfahren, *Anoplophora chinensis*, holzzerstörende Insekten

1 Introduction and objectives

As a result of globalization and international trade of plants for planting, tree destructive pests are arriving European regions from countries around the world (Rabitsch, 2010). Since several years exotic wood-boring insects such as the Citrus Longhorned Beetle (CLB), *Anoplophora chinensis* Forster form *malasiaca* (Coleoptera: Cerambycidae) have been detected repeatedly in European Union (EU) member states at imported young trees (Cocquempot and Lindelöw, 2010).

CLB is a devastating organism on *Citrus* and ornamental trees in its native range in Asia and is able to be spread undetected within Bonsai and plants for planting. Host plants cover a wide range of deciduous tree species (Schröder and Maspero, 2008). CLB is classified as quarantine pest in the EU. Infestations and outbreaks have been detected in Italy (established (EPPO, 2006c)), France (eradicated (EPPO, 2006b)) and the Netherlands (eradicated (EPPO, 2006a)) as well as findings of single beetles in different regions of Germany and in Switzerland (Hérard et al., 2006).

According to the import prescriptions of the Commission Implementing Decision 2012/138/EG import inspections have to include destructive sampling of a specified amount of plants (EU, 2012). The background is that infestations with CLB almost show no external symptoms for identification by visual inspection. Destructive sampling by hand using rose scissors is time consuming, risky for the inspector and destroys parts of the plant consignment. Therefore efforts are underway for assessment and development of new technologies for efficiently but non-destructive inspection of plants.

In the current study infrared thermography was investigated using wooden samples of three European tree species (*Acer platanoides* L., *Acer pseudoplatanus* L., *Salix alba* L.) to capture thermal images of surrogate wood-boring larvae (*Cossus cossus* L.) and larval galleries, as well as borings inside the cavities at long-term measurements. Furthermore, the attempt was to visualize larval motions and activities based on differences in their temperature in comparison with ambient test objects.

Non-destructive testing

The method of non-destructive testing of material is a steady educing process (Brashaw et al., 2009), founded by simple mechanical handlings (for example taping of ceramic) in prehistoric times. However, the economic meaning by implementation of physical applications for material inspection is relative young and engendered by magnetic methods in 1868 (Müller, 1975).

In the background of worldwide ascending "emphasis to addressing forest and ecosystem health issues" (Brashaw et al., 2009) and its management for economical utilization of woody biomass, currently global research is conducted to verify capabilities of non-destructive testing technologies for assessment of wood and wood-based material (Brashaw et al., 2009).

The first and even today used non-destructive evaluation method of wood is the visual inspection. Joining the development of scientific non-destructive testing in the early 20th century and the aim for assessment of wood properties by theory of elasticity, a number of technologies using mechanical behaviour and electromagnetic radiation established for characterization of wood have been developed (Bucur, 2003a; Bucur, 2003b).

For the current study the major limitation factor of non-destructive techniques is the material behaviour at the date of observation. The trees to be investigated are living but in dormant stage, whereas objects described in the mentioned test methods were either dried, larger or standing with liquid transport processes. Furthermore the defect can differ concerning size and distance to objects surface and important physical characteristics.

Given the stated factors above, no non-destructive techniques described in the literature to identify insects within young deciduous trees. Little evidence was given for detecting insects respectively holes, cracks or knots inside of wooden material and standing trees. A few methods deal with locating and tracing of high amount of insects and other pests and diseases (incl. fungal degradation), inducing altering processes of wooden objects.

No methods have been assessed on its applicability on young wooden plants with stem diameters at the root collar of less than five cm. However, with respect on small-scaled and cut wooden materials and entomological backgrounds, few non-destructive techniques have been observed more or less successfully at least: Micro-computed tomography and wood wasp larvae (Jennings and Austin, 2011) computed tomography and house borer larvae (Krajewski et al., 2005), ground penetrating radar and house borer larvae (Sachs et al., 2008) and noncontact ultrasound and cotton wood borer (Fleming et al., 2005).

Infrared thermography (IR-thermography) was chosen for the current study with the aim to detect larval galleries and insect stages in young plants. The technique was already used in the framework of decay detection on standing trees (Catena, 2002; 2003; Catena and Catena, 2008) and successfully assessment of wood properties (moisture content, structure, density, etc.). It was also part of investigations for displaying internal heterogeneities (defects, decay, delaminations, knots, etc.) in lumber and wood-based material (Kline et al., 1992; Murata and Sadoh, 1994; Masuda and Takahashi, 1998; Quin et al., 1998; Wyckhuyse and Maldague, 2001; Ludwig et al., 2004; Meinlschmidt, 2005; Kandemir-Yucel et al., 2007; van Dyk and Lemaster, 2010; Aderhold et al., 2011). Active thermography was particularly applied for detecting galleries of wood worms, *Anobium punctatum* L. (Coleoptera: Ptinidae), in a dried lath at the Fraunhofer Institute for Wood Research, Wilhelm-Klauditz-Institut (Fig. 1).

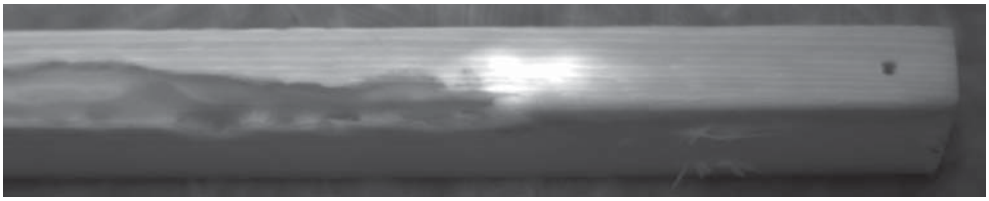

Fig. 1. Detected galleries of a wood worm, *Anobium punctatum* L. (Coleoptera: Ptinidae), in a dried lath using active thermography (WKI intern).

Background of infrared thermography

Since applications of IR-thermography developed in the 1960th in civil sector, it was primary used to monitor thermal bridging in buildings and overheating processes, for example of engines and devices in electronic and energy industry. Today several utilizations in metrology and especially quality management can be observed. Further applications are found in air-conditioning, medicine, remote sensing, environment analysis, process monitoring in the meantime (Maldague, 2001; InfraTec, 2004; Grote, 2009).

IR-thermography is described as a nondestructive, noncontact (and nonintrusive when passive) detection technique for imaging of temperature-dependent (thermal) radiation. By implementation of surface temperature distribution it can be used for assessment of structural and behavioural patterns under object surface (Maldague, 2001). IR-thermography benefits that objects with temperatures above absolute zero (0 K or −273 °C) emit individual electromagnetic radiation (*thermal* or *Planck´s radiation*) caused by inner molecular motion. This radiation, also called *infrared*, is located above visible spectrum (0.35–0.74 µm wavelength) and cannot be sensed by human eyes at common ambient temperature. For visibility and measurements of thermal distribution on objects surface and also for discovery of blemishes infrared cameras (or thermal cameras) are used (Aderhold et al., 2005; Aderhold et al., 2011).

The thermal radiation has to pass more or less long distances from measuring object to instrument (IR-camera). This way through media could affect results whereas transmission strongly depends on wavelength. Caused by atmospheric (air) absorption (radiant uptake), especially by steam and carbon dioxide, measurements between 0.4 µm and 30 µm wavelength are inappropriate for long distance. To minimize falsifications in results, the usage of three spectral bands with higher transmission in an "atmospheric windows" at 0.4...0.8 µm (1: Visible [VIS]), 3...5 µm (2: Mid infrared [MIR] or Mid-wavelength infrared [MWIR]) and 8...12 (14) µm (3: Long-wavelength infrared [LWIR]) for thermographic observations is common (Breitenstein and Langenkamp, 2003; InfraTec, 2004; Schuster and Kolobrodov, 2004).

Aderhold and Meinlschmidt (2005 and 2011) distinguish between measurements of emissivity differences and temperature differences. Latter deal with heat flow properties at warming or cooling processes, called *heat flow thermography*, and is most common nowadays. In characterizations of Maldague (2001) infrared thermography is basically classified in *passive* and *active* thermography, containing both attributes: emissivity and heat flow.

The term "thermography" is commonly used individualized when applying ***passive thermography***. Features of investigation are naturally higher or lower energized than environment and emit thermal radiation (Maldague, 2001). In simply cases the cool-down period of objects is process-related and only be observed with a thermographic camera. Surface areas with trapped vacancies decrease heat flow and refrigeration will occur faster, due to reduced heat flux from inside. Application examples are delaminations or air inclusions (Aderhold and Meinlschmidt, 2011).

When heating or cooling processes are not integrated in manufacturing the measuring objects has to be stimulated by heating impulse immediately before or while observation (***active thermography***). Simple case is an electric heater passing conveyer. Heating front invades the object while surface is cooling down. When passing vacancies the heat flow is disabled hence surface above these blemishes will be longer warm (Aderhold and Meinlschmidt, 2011). The speed of invading heat is an important factor and depends on thermal properties like density, heat capacity, thermal conductivity and the bonding quality between top surface layer and the base material. Subsurface anomalies will decrease the surface temperature more slowly (Meinlschmidt, 2005). Common processes of active IR-thermography follow with optical impulse, maybe halogen lights, laser or radiant heater. Larger pulse duration is adapted for detecting large depth or materials with lower heat conductance basically. However, when objects surface (reflection) is high reflected or when measurement is not possible due to geometric(s) reasons (inspection of cavities), hot or cold mediums (for example air) can be supplied for analyses (Aderhold and Meinlschmidt, 2011).

The general setup of both thermographic methods used in the current investigation (active and passive) is shown in Fig. 2.

2 Material and methods

Because *Acer* species have been observed to be a preferred host tree for CLB in the known infested areas in the EU, this species was chosen for the model plants. This was supported by the fact that *A. palmatum* originating in China was the common species where CLB have been found during import inspection. Due to its quarantine status and the knowledge that CLB attacks native *Acer*

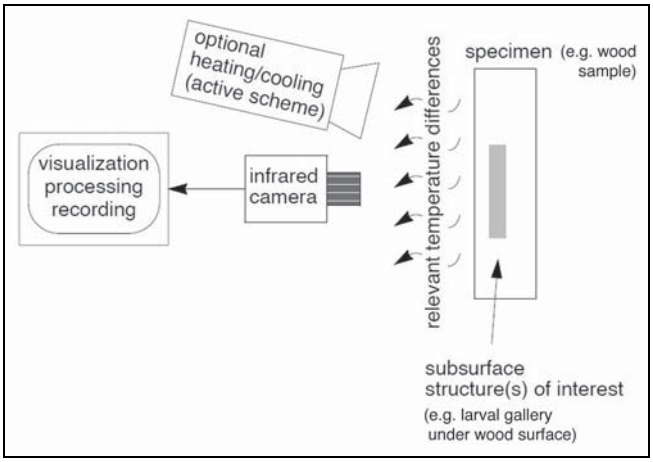

Fig. 2. Schematic setup of infrared thermography for nondestructive testing, adapted from (Maldague, 2001).

trees, it was decided to develop a pest/host model system using both *Acer* as native tree species and surrogate larvae of a native wood boring insect.

Model organism

The native species, *Cossus cossus* L. (Lepidoptera: Cossidae), was used as a surrogate for the studies (model organism). The goat moth´s larvae show similar symptoms concerning larval and borehole size and host plant spectrum in comparison to CLB, though the species is a moth and not a longhorned beetle. *C. cossus* passes 8 larval stages up to 10 cm length in adult stage. It drills oval boreholes up to 2 cm in diameter in its major host plant genera similar to those used by CLB such as *Acer* L., *Salix* L., *Populus* L., *Fagus* L. and *Betula* Mill.

The goat moth larvae (at least 4 different larval sizes) were collected in June 2011 from an infested goat willow tree (*Salix caprea* L.) near Brunswick in Germany. The larvae were reared under laboratory conditions at mean temperature of 18°C and 60% rel. air humidity in separated glass jars. According to Friedrich (1983) the goat moths were fed by dried granary bread and quartered apple pieces on saw dust used for animal bedding which functioned as soil substrate and wintering ground.

A second insect species, the native meal worm, *Tenebrio molitor* L. (Coleoptera: Tenebrionidae), was used for preliminary tests though they are not related to wood. Larvae had a length of up to 30 mm in total.

Model plants

To be able to work with more or less homogenous, defect free, standardized test plants it was decided to use "model plants" in the form of the most affected part of CLB which is the lower part of the trunk. The wood samples *Acer pseudoplatanus* L, *Acer platanoides* L. and *Salix alba* L. were obtained by harvesting three to eight years old trees in a forest near Northeim in Germany. Shoot axes were prepared after cutting into 250 mm long samples with three diameter classes (Tab. 1). For this experiment, three

Tab. 1. Stem and borehole diameter classes of model plants

Stem diameter		Borehole diameter	
class	diameter [mm]	class	diameter [mm]
A	10 – 20	a	2
B	21 – 30	b	5
C	31 – 40	c	10

different holes sizes with a length of 150 mm were drilled into the samples in axial direction (Tab. 1). For control, the end of the borehole inside the sample was marked by an outer line.

To simulate living plants the usage of green wood was required. For this purpose and to prevent losses of wood moisture the end faces of the samples were sealed with paraffin wax (Sigma-Aldrich Germany, Paraffin wax congealing range 45–50°C) and subsequently stored in air-sealed plastic bags at 6°C. All samples were adapted to room temperature 24 hours before thermal measurements.

The moisture content of the wood was determinate according to DIN 52183 (1977) via gravimetric assessment after thermographic measurements. The samples were placed in a forced-air oven (Memmert, Type UL50, Schabach, Germany) maintained at 103°C until reaching a constant ovendry weight basis.

For detection of larvae or larval motion inside the wood, goat moth larvae were artificially inserted in boreholes with diameters of five (b) and 10 mm (c).

Thermographic equipment

The investigation was carried out in a stepwise approach. In a **first preliminary test** two infrared imaging cameras a VarioCAM® hr research 600, (Jenoptik, Germany) and a ThermaCAM™ B20 (FLIR Systems GmbH, Germany) were used to verify if meal worms can be identified in adequate contrast to background. Furthermore thermal images of wooden samples with boreholes and inserted larvae were taken and analyzed. A **second preliminary** investigation was conducted for observation of time-depending cooling processes of samples (*A. pseudoplatanus*) and boreholes induced by different heating procedures by active thermography. For this purposes three heating sources were applied: blow-dryer, infrared carbon emitter, and black body emitter.

For assessment of larvae´s motion activities and quantifiable inspection in wooden samples, **two long-term measurements** about 1) 20 h and 2) 24 h were run with a high-performance thermographic dual-band system Geminis 327 k ML (IRCAM GmbH, Germany, 3.7–5.0 µm and 8.0–9.4 µm), used in metrology, research and industry, at the Fraunhofer Institute for Wood Research in Brunswick. Pre-investigations approved a higher contrast and granularity in LWIR range compared with MWIR range. The technical data of all applied cameras are described in Tab. 2.

Tab. 2. Main feature of IR imaging cameras

	VarioCAM® hr research 600	ThermaCAM™ B20	Geminis 327k ML (dual – band)
Spectral range	7.5 – 14 µm (LWIR)	7.5 – 13 µm (LWIR)	3.7 – 5.0 µm (MWIR) 8.0 – 9.4 µm (LWIR)
Resolution	30 mK at 30°C	100 mK at 30°C	15 mK (MWIR) 25 mK (LWIR)
Measuring range	–40 – 1200°C optional 2000°C	–40 – 500°C	n.a.
Absolute measurement accuracy	± 2°C or ± 2%	± 2°C	n.a.
Image size	640 × 480 pixel	320 × 240 pixel	640 × 512 pixel

The goal of **long-term measurement 1** was to determinate activities of four larval stages of *C. cossus* accompanied by differences in temperature. Furthermore the assessment of maximum divergences of thermal properties between background objects (wood chips, apple and solid wood) and larvae has been studied during 20 hours.

Four goat moth larvae with various body sizes (Tab. 3) were placed in a plastic box covered with wood chips, solid wood pieces (*S. caprea*) and quartered apple. The thermography set-up was positioned directly above and focused on the test objects. After recording the thermal imaging video, 10 representative pictures of the 20 h lasting film were chosen for detailed thermal assessment. The acquisition of data and evaluation of temperature was done by thermal determination lines that were defined for each picture and each test object.

The second observation (**long-term measurement 2**) aimed for precisely identifying and determination of larvae´s activities inside natural host material. Additional goal was to detect boreholes without larvae. Pre-drilled (10 mm borehole diameter) wooden samples (*A. platanoides*, *S. alba*) were inserted with *C. cossus* larvae of higher development stages between 60 and 100 mm body length. For obtaining different activation status, and for assessing effects of bore dust or strands, larvae were instated at different times: 1) 20 days before (boreholes filled with bore dust at the time of measurement) and 2) immediately before starting thermal measurements (boreholes without bore dust at the time of measurement). For control of larval behavior and to get insight at any time, two samples were divided in center in longitudinal direction and then bonded with tape before imaging.

Eight samples (stem diameter 20–42 mm) fitted with one goat moth larvae each were placed in a 40 × 25 × 25 cm glass container, which, to minimize means of escape, sited in a major plastic box (Fig. 3). At this, six wooden samples were chosen and two furthermore lar-

Tab. 3. Test objects of long-term measurement 1

test object	characteristic	code
background 1	wood chips, apple	b1
background 2	solid wood (*Salix caprea*)	b2
larvae 1	100 mm (length)	l1
larvae 2	70 mm (length)	l2
larvae 3	50 mm (length)	l3
larvae 4	30 mm (length)	l4

Fig. 3. Setup for long-term measurement 2.

vae functioned as control for larval temperature outside of samples. In total, eight representative pictures served as the basis for determining of temperature profiles of eight test objects (Tab. 4).

The thermal determination lines were located in center axis in axial direction along the total sample over each frame. Larvae 1 and 2 were scaled over its longest straight-line when larvae was visible (Fig. 4).

The thermal determination lines illustrated the output values and represented the absolute temperature at measuring point. One pixel confirmed one measuring point of determination line and resulted in 0.035 cm per pixel (one value of temperature per pixel).

Statistical Analyses

Statistical analysis was carried out using SigmaPlot 11.0 (Systat Software Inc., USA). At **long-term measurement 1**, mean comparison between each test object at observation time was realized by t-test, when both groups were normally distributed, or *Mann-Withney* u-test, when one group showed no normal distribution. The chosen p-value was defined at significance level of $p = 0.01$.

The **second long-term measurement** used fixed determination lines for tracing abnormalities or outliers in temperature that would be induced by larvae in center regions of wood specimen. Evaluation had been done by analyzing of temperature profiles along each test object per picture.

3 Results

Results of **preliminary test 1** revealed that meal worms could be recognized by thermal imaging under laboratory conditions. Both standardized passive systems VarioCAM® hr and ThermaCAM™ B20 identified organisms when larvae were on surface of background and no external objects blocked intermediately the thermal scans. However, in dependence of physical properties of the background the total measured temperature differences between larvae and background were very low and under 0.5 K. Highest contrast of approximately 1 K was captured between cold underground of plastic container and moving larva. In contrast, temperature changes between wood chips or solid wood and organism were vanishingly low. Furthermore neither boreholes (2, 5, and 10 mm in diameter) nor larvae inside holes could be visualized by given passive thermal systems. Zones with cavities and inserted organism had no measurable effect on surface temperature.

Tab. 4. Test objects of long-term measurement 2 (wood samples [*Salix alba*, *Acer platanoides*] with inserted *Cossus cossus* larvae; larva 1 and 2 outside of specimen for control)

test object	wood			larva		code
	tree species	diameter [mm]	borehole characteristic	larval size [mm]	larval time in wood	
sample 1	*Salix alba*	22	bore dust	60	20 days	s1
sample 2	*Salix alba*	42	bore dust	90	20 days	s2
sample 3	*Salix alba*	20	no bore dust	80	0 days	s3
sample 4	*Acer plat.*	25	no bore dust	80	0 days	s4
sample 5	*Salix alba*	36	bore dust	100	20 days	s5
sample 6	*Acer plat.*	33	no bore dust	90	0 days	s6
larva 1	–	–	–	80	–	l1
larva 2	–	–	–	60	–	l2

Fig. 4. Thermal test setup of long-term measurement 2. Solid wood samples (*Acer platanoides*, *Salix caprea*) with axial boreholes in center and inserted *Cossus cossus* larvae in each sample. Left: Color image with marked positions at the end of boreholes. Right: Thermal image with measurement setup of thermal determination lines (s1 to s6). Test object l1 shows one of two "free" larvae.

Similar results were given at **preliminary test 2** when active heating via blow-dryer, infrared carbon emitter and black body emitter and measuring following cooling behaviour. Even by using the high sensible dual-band camera Geminis 327 k ML no alternation between treated and untreated wood sections could be visualized by heating impulses and active thermography.

Long-term measurement 1: *Cossus cossus* larvae could be displayed at 20 hours observation in thermograms when moving on the surface of background objects. As seen in Fig. 5, larvae (l1–l3) appear brighter, hence warmer, compared to the colder wood chips and apple ground (b1). In contrast, temperature differences between larvae (l4) and solid wood (b2) were evanescent low, whereas wood samples even increased in level. At later points of view (especially at night), larvae showed reduced motion activity and decreased temperature changes. The detection even on background 1 was aggravated crucial.

This assessment is confirmed by analyzing mean temperature data of determination lines (Fig. 6). Viewing the complete test objects, in particular background 1 was exhibited in relatively low mean temperature. Consequently the highest difference of 0.164 K was given comparing background 1 (minimum temperature of 22.89°C) and background 2 (maximum temperature of 23.055°C). Divergences between background 1 and larvae were marginal ranged anymore, from 0.093 to 0.16 K. In addition mean variances among background 2 and larvae emerged in values smaller 0.071 K, liminal in measurability.

A confrontation of temperatures of larvae 1–4 resulted in very low divergences at thermal analyses and is ranged between 22.984°C to 23.051°C. In terms of larval size, the highest temperature could be recognized at the biggest larva 1; lowest value was given at the smallest larva 4. However, overall no distinct trend of differences in temperature was ascertainable, that could draw inferences from larval size to temperature changes.

Statistically mean comparison confirmed no statistical significances between all groups using significance level $p = 0.01$. Overall only small differences in temperature between each group of test object can be recognized. By comparison of background 1 and larva 1, a maximum mean difference of 0.16 K is been listed ($p = 0.041$). Residual groups resulted in lower differences ($p < 0.05$). The smallest divergences are given by relating solid wood and larva 1. As a consequence, larvae and background objects could not be imaged or differentiated adequate by thermal measurements.

By consideration of individual frame (point of view) it is recognizable that maximum differences in temperature between larvae and background 1 occurred in relatively high values (0.18 K) a few time after starting measurement. The divergences fell down at night to acquire a minimum level (< 0.05 K) when larvae reduced movement. The measurement was largely impossible, when larvae were hidden behind backgrounds or totally stopped motion. The highest variances were given during the next day (0.35 K) after 15 hours measurement.

Long-term measurement 2: Inserted goat moth larvae could not be visualized by thermal dual-band equipment inside of solid wood samples at 24 hours recording. Thermograms displayed no measurable temperature changes in marked areas, where larvae had been positioned. Over the whole samples, so including larval motion along total borehole regions, no increases in temperature could be recognized.

Additionally no differences in density, affected by abnormalities between solid wood and borehole or solid wood and bore dust, could be detected in thermograms.

As illustrated in Fig. 7, as an example of one measurement, a rapid reduction in temperature at edge regions, displayed in blue ranged areas in thermogram, could be identified. Caused by water less at front plane induced by

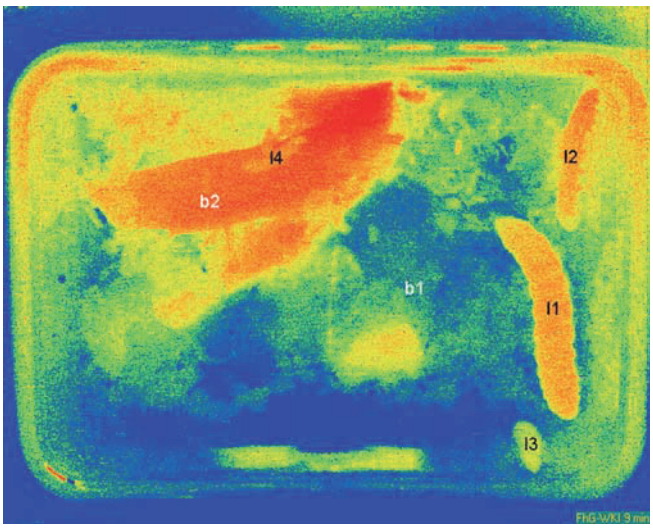

Fig. 5. Thermogram 1 at 9 min at high larval activity in shortly after beginning 20 hours long-term measurement 1. b1 = background 1 (apple, wood chips), b2 = background 2, l1 = larva 1 [100 mm], l2 = larva 2 [70 mm], l3 = larva 3 [50 mm], l4 = larva 4 [30 mm]. Adequate differences in temperature between larvae and b1. Inadequate differentiation between solid wood and l4.

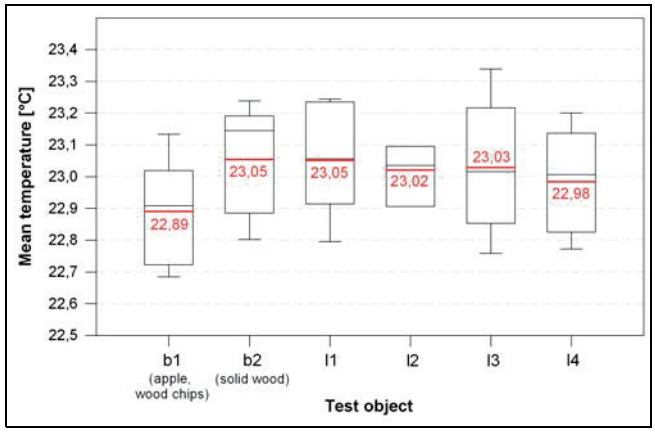

Fig. 6. Mean temperature of test objects (b1 = background 1, b2 = background 2, l1 = larva 1 [100 mm], l2 = larva 2 [70 mm], l3 = larva 3 [50 mm], l4 = larva 4 [30 mm]) at long-term measurement 1; averaged by determination lines.

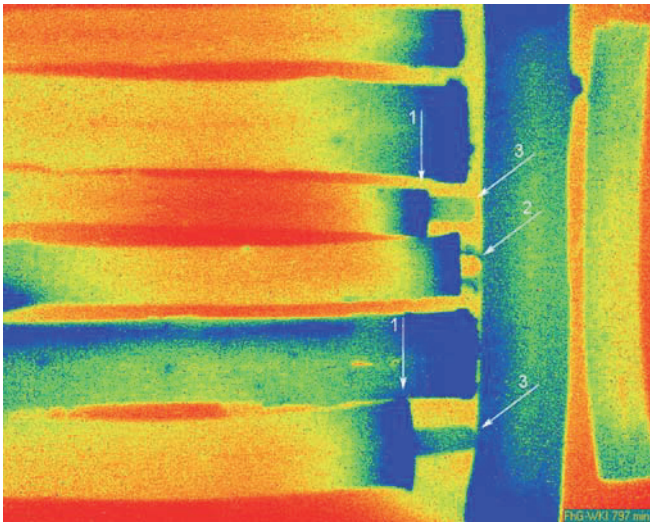

Fig. 7. Thermagram of evaluated frame of long-term measurement 2. Solid wood samples (*Acer platanoides*, *Salix caprea*) with axial boreholes in center and inserted goat moth larvae (*Cossus cossus*) in each specimen. 1: blue regions resulted from cooling processes induced by evaporation at front plane. 2: "head" of a moving larva with bore dust around. A back segment inside of wood was not recognizable. 3: Plugs for preventing larval escape (not to be confused with larvae).

evaporation, regions cooled down unleashing decreases of temperature (arrow 1 in Fig. 7). Due to adequate differences in temperature, anterior parts of moving larva with bore dust around were successfully identified outside of specimen by thermal imaging. However, back segments, hidden in wood specimen, were not recognizable (arrow 2 in Fig. 7).

Mean temperature profiles in center regions of specimen samples could not reveal temperature changes that would be initiated by body emissions of *Cossus cossus* larvae or given boreholes and -dust. Overall similar, homogenous trends of temperature and no abnormalities could be detected. Regardless of whether sample or frame (point in time) has been observed, the maximum differences in temperature remained always below 0.5 K (in most cases ranged between 0.2–0.3 K) at the particular specimen. The trend of temperature along the wooden axles is displayed by using two examples of frames in Fig. 8. To minimize falsifications in data analyses caused by evaporative cooling, last pixels close by front planes had to be removed from investigation.

As illustrated in Tab. 5, arithmetic averaging of data per sample resulted in means between 21.059°C (sample 5) to 21.224°C (sample 3). Standard deviations resided below 0.070°C for each specimen.

Single frames also eventuated in relatively homogeneous values without remarkable variances between samples. It is notable that the measurement started with highest absolute temperatures to change into minimum at night (frame 5 and 6). Additionally even larvae outside of specimen (control) showed marginal variances compared to samples (Tab. 5).

4 Discussion

The evaluation of the experiments using goat moth larvae as model organism and typical hardwoods do not support hypothesis that infrared thermography can be used for detecting insect larvae, boreholes or bore dust within green solid wood.

Larval motion and presence do not affect temperature changes of specimen samples. Due to poikilothermic behaviour of most insects, larval motion (motor) activity (muscle activity, regulation of nervous system) depends on ambient minimum temperature. Although a few species have specific regulation systems for independent heating body temperature and above ambient temperature (for example *Sphingidae*, *Bombus*), most insects are

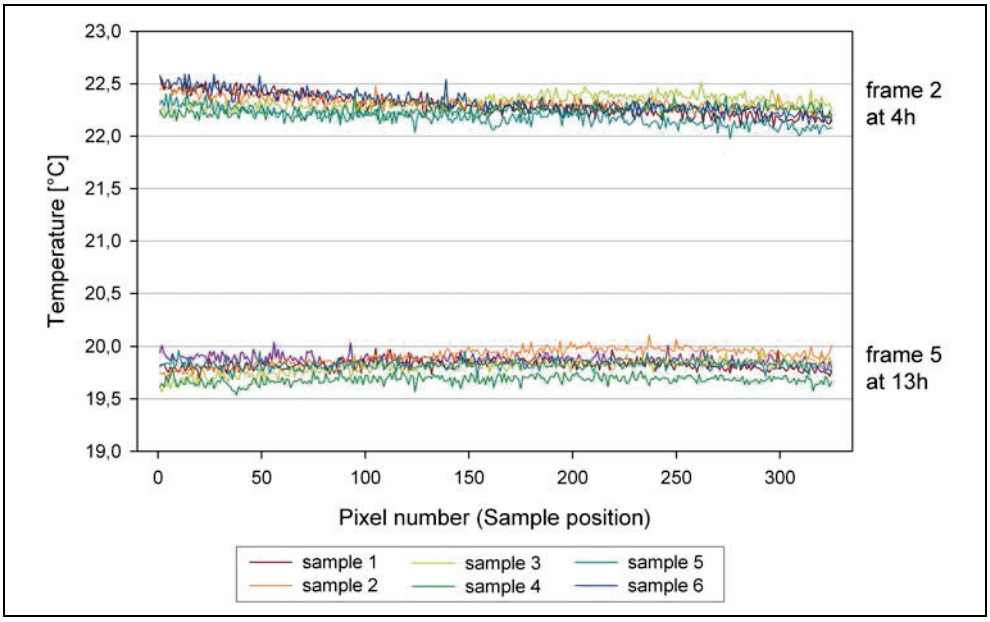

Fig. 8. Axial temperature profiles along the center of wood samples 1–6 with boreholes and inserted *Cossus cossus* larvae at 24 hours long-term measurement 2. Two examples are represented: Frame number 2 (after 239 min; at daytime) and frame number 5 (after 797 min; at night). No measureable effect of temperature change induced by larvae, boreholes or bore dust was verified.

Tab. 5. Mean temperature of test objects per frame at long-term measurement 2. Sample 1–6: Solid wood samples (*Salix alba* and *Acer platanoides*) with borehole (10 mm in diameter) and *Cossus cossus* larva inside. Larva 1 (80–90 mm length) and larva 2 (60–70 mm length): Control – *Cossus cossus* larva outside of sample, when visible

	test object							
	sample 1	sample 2	sample 3	sample 4	sample 5	sample 6	larva 1	larva 2
frame 1 (116 min)	22.946	23.046	23.027	22.954	22.913	23.058	22.909	n.a.
frame 2 (239 min)	22.297	22.317	22.331	22.241	22.180	22.322	22.256	n.a.
frame 3 (330 min)	21.581	21.646	21.705	21.596	21.520	21.665	21.723	n.a.
frame 4 (524 min)	20.147	20.193	20.307	20.197	20.097	20.205	n.a.	20.277
frame 5 (797 min)	19.876	19.824	19.907	19.805	19.682	19.826	n.a.	n.a.
frame 6 (822 min)	19.965	19.921	19.988	19.904	19.762	19.907	n.a.	n.a.
frame 7 (1232 min)	21.053	20.992	20.982	20.929	20.863	20.998	21.047	20.827
frame 8 (1349 min)	21.670	21.606	21.548	21.513	21.457	21.625	21.631	n.a.
Total (1440 min)	*21.192*	*21.193*	*21.224*	*21.143*	*21.059*	*21.201*	*21.901*	*20.392*

adjusted to environment (Hoffmann, 1978). In this case our *Cossus cossus* larvae largely adapted to temperature in solid wood and environment (ambient temperature and backgrounds) and no thermal energy modifies surface temperature.

According to preliminary tests and long-term measurement 1, larval temperature is minimally affected by activation energy. Larvae had been stressed induced to increasing motion, when starting or ending the experiments. Hence, the temperature changes occurred in relatively high values (but even below 0.5 K in average) and larvae could be identified when organisms were moving on top and no external objects blocked intermediately the thermal scans. Active larvae (for example when climbing along the box wall) showed higher temperatures compared to motionless individuals.

An additional factor for maximum variances could be found by cooling effect as a result of evaporation. Hellebrand et al. (2005) verified that fungal infected wheat plants with higher transpiration have reduced body temperature compared with healthy plants. Thus, the high water content of apple and its passing to adjacent wood chips (background 1), inducing evaporation processes affected in a decrease of temperature. This phenomenon was also given at front planes of wood samples at long-term measurement 2 (Fig. 7).

Over the course of observation, especially at night, animal functions turned down and body temperature adapted to ambient objects in a higher level, thus a differentiation was more difficult. Compared with visual assessment (for example by photo camera), that recognized moving larvae via basic color contrast, thermal imaging is no appropriate application for larvae detection on surface.

Furthermore it could be illustrated that larvae could not be identified inside of wooden model plants at long-term measurement 2. The same result was given at the first long-term measurement when larvae were hidden below solid wood or soil background. Thus, the effect of thermal adaptation on environment may superimpose the effect of motion activity and is insufficient for revealing.

As a second result no differences in surface temperature will be initiated by variances in density (holes, cavities, dust) inside of hardwood samples. Zones with cavities and bore dust have no measurable effect on surface temperature.

An explanation for this phenomenon could be given by internalization that specimen samples had indeed similar water content to living trees, but no (living) reactive tissue that could affect water flux. Hence a measurable difference in thermal conductivity to hidden zones (decreasing by reduction of liquid content) is not given (Catena, 2003).

The effect of water is one of the most limiting factor by using active IR-thermography in wooden materials via heating sources (blow drier, IR emitter, halogen spotlight). In conditioned, moist model samples of *Acer pseudoplatanus* primary bark tissue and components accumulate water, protect water loss and increase moisture. Water has very high thermal capacity and is able to storing heat well (Lillesand et al., 2008). Hence the

heated samples have long cooling duration and imitate boreholes do not affect the cooling process.

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