

In addition, we should focus on developing grain drying technologies and devices that could be used and adopted easily by farmers. Farmers should be guided to carry out grain harvesting operations scientifically and reasonably, and do a good job at grain quality control.

#### **4. Quality Control Requirements during Grain Storage**

By taking advantage of good correlation between fatty acid and taste score, fatty acid value could be used as a sensitive indicator of daily monitoring of grain quality changes in order to monitor in a timely manner stored grain quality. We should pay special attention to parts of bulk grain, sensitive parts, and monitor in a timely manner, and to examine with reasonable scientific and technical measures, including related technologies and equipment, to improve "overall" quality control of stored grain.

#### **5. Importance of Grain Quality Control**

Guaranteeing grain quantity and quality are complementary. Guaranteeing grain quantity is relatively intuitive and tangible. However, maintaining quality, involving the biological and non-biological ecological environment of a grain bulk, is challenging. In order to control the physiology and biochemistry, molds, pests and other ecological factors of grain storage, it is necessary to strictly control grain quality during warehousing. At the same time, based on market oriented rules, we should strengthen the implementation of proper grain storage technologies to achieve the requirements of grain quality control, to meet the needs of grain consumption, and to ensure the high value of stored grain.

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### **A new approach to acoustic insect detection in grain storage**

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DOI 10.5073/jka.2018.463.077

#### **Abstract**

Insect pests in grain storages can cause severe financial losses. Infested grain needs to be treated and can be sold only with lower profit. Intense infestation can lead to contamination with mycotoxins and total loss of stock. Therefore, an early detection of insect storage pests is of great importance to farmers and storage keepers but is difficult to obtain in large amounts of grain.

Besides conventional detection methods such as insect traps and monitoring of temperature and relative humidity, acoustic monitoring can identify insect infestation. Insects in grain and other stored products produce sounds at a low level during movement and feeding activity. A new acoustic system was developed as part of the project "InsectTap" to increase the detectability of insect sounds. Highly sensitive microphones were installed inside a metal tube that increased the surface on which beetle signals could be detected. Additionally, the tube worked as a beetle trap recording all sounds from even one single beetle inside the trap.

The tube system was tested in 1 and 8 m<sup>3</sup> boxes filled with wheat. Infestation could be detected at a very early stage about 8 weeks before a temperature rise, or beetles at the grain surface indicated an infestation.

In the next step, this "Beetle Sound Tube"-System will be installed in different grain silos aiming for automatic early detection and specific identification of infestation. The information provided to the farmer or storage

keeper allows early and specific treatment to reduce losses. Additionally, the introduction of parasitoids via the tube system will be tested to increase the efficacy of biological control.

**Keywords:** Acoustic Detection, Monitoring, InsectTap, Beetle Sound Tube, *Sitophilus granarius*.

## Introduction

Early detection of insect storage pests is important to reduce losses and preserve high quality food. Recognition of infestation in large amounts of storage goods is difficult, and in many cases it is only noticeable when the amount of insects increases considerably and causes a rise of temperature and relative humidity. At this stage, mites and mould can lead to major secondary losses.

Treatment of insect infestation has become more difficult due to a decrease of available chemical substances for storage protection, an increase of organic farming that cannot use chemical agents and the increasing disapproval of consumers to chemical treatments. Therefore, early detection is crucial to have a choice between different non-chemical treatments that are not suitable for mass infestation.

Besides measuring temperature and relative humidity, using traps or sieving samples, the detection of feeding and movement sounds is another way to discover insects in stored goods. A great advantage of acoustics is that even the sounds of hidden stages of insects can be detected (Leblanc et al., 2009). But very low amplitudes of signals and sound insulation properties of grain make it difficult to detect the sounds at distances of more than a few centimetres (Hagstrum and Subramanyam, 2006).

Another difficulty that devices for acoustic detection of insects face are settlement sounds of grain that can be mistaken for insect sounds. Therefore, a permanently installed acoustic system could have advantages (Hagstrum and Subramanyam, 2006) compared to mobile probes or acoustic test containers.

Aim of the project "InsectTap" funded by the Federal Ministry of Food and Agriculture (BMEL) was the development of an acoustic early detection system that allows detection and specific identification of insect infestation. Experiments under controlled conditions showed as a first result discriminability of a number of adult beetle species by sound (Kirchner et al., 2016).

Another part of the project that will be described in this paper were pilot plant scale experiments in 1 and 8 m<sup>3</sup> of stored wheat using high-sensitive microphones placed inside metal tubes to increase the detectability of insect sounds due to surface enlargement.

At the next step, this "Beetle Sound Tube"-System will be customized to the needs of farmers and keepers of small storage facilities and installed in different sized grain silos aiming at automatic early detection and specific identification of infestation. The information provided to the farmer or storage keeper allows early and specific treatment to reduce losses including the application of parasitoids via the tube system to allow easier access to the infestation.

## Materials and Methods

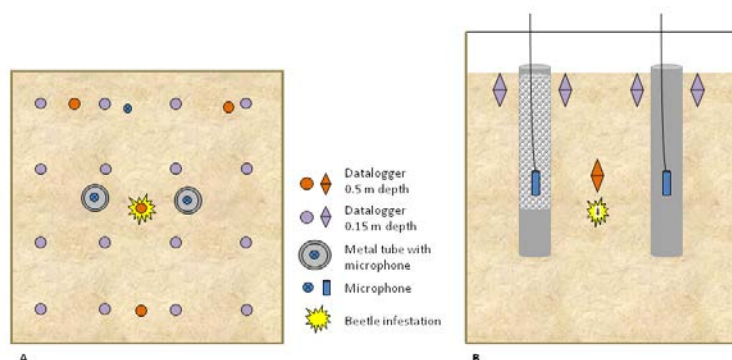
### Experimental set up

Two experiments were carried out using large wooden boxes of 1 or 8 m<sup>3</sup> filled with wheat. The boxes placed inside an about 77 m<sup>2</sup> storehouse were equipped with 17 to 20 data loggers (EasyLog EL-USB 2) to record temperature and relative humidity and 3-4 microphones for acoustic measurements.

During the first experiment using the 1 m<sup>3</sup> box (Fig. 1), three free field condenser microphones (PCB-378B02, PCB Piezotronics, Depew, USA) were used under different conditions. The microphones were either covered with a layer of PET rescue foil as dust protection and placed directly into the wheat or were suspended inside 0.75 m long galvanised steel tubes of 0.08 m diameter inserted into the wheat to focus sound signals from the surrounding substrate. While one of the tubes was a simple metal tube with a stainless steel lid at the bottom, the second tube was equivalent but with

a large number of 2.5 mm drilled holes and functioned as a beetle trap comparable to a WB probe trap (Barak et al., 1990) with a removable cup containing some grain at the lower end of the tube for accumulation of beetles. In the 8 m<sup>3</sup> experiment, four metal tubes of 1 m length and 0.1 m diameter were used from which one functioned as a trap.

The experiment in the 1 m<sup>3</sup>-box was carried out between May and October 2016, while the 8 m<sup>3</sup> box was used from March to August 2017. At the beginning of both experiments, 200 wheat kernels containing larvae of the grain weevil (*Sitophilus granarius*) 25-28 days or 30-32 days after oviposition, respectively, were introduced at one position in the box. A data logger for temperature and relative humidity was placed directly above the position of insect infestation.



**Fig. 1** Experimental set up of the 1 m<sup>3</sup> box. **A:** Top view of the box showing the positions of the three microphones, 20 data loggers and the position where the beetle infestation started. **B:** Lateral view with the two microphones in the two tubes (left tube functioned as a trap), data loggers and position of beetle infestation.

For the following months, temperature and relative humidity were logged every six hours. Acoustic data were recorded at the first 20 minutes of each hour using an IMC CS-3008-N High-resolution measurement device (imc Meßsysteme GmbH, Frankfurt, Germany) connected to a laptop using IMC Studio Pro 4.0 software. Additionally, the number of beetles in the trap was determined and the insects removed on a regular basis.

### Acoustic evaluation

After it was checked that there was no daily rhythm in granary weevil activity, three times per day were chosen for acoustic evaluation (3 and 9 a.m., 9 p.m.). The times were chosen to include one recording during daytime, one during twilight and one during night-time. During daytime disturbance due to workers and traffic in the surroundings were common. In twilight there was less traffic, no working activity but natural sounds such as birds, while during night-time external noise was low unless the weather situation was rough.

The recordings were bandpass filtered (1000-12000 Hz using IMC FAMOS Professional 7.0) to reduce background noise. Four 15-second segments of the recording starting at minute 1, 6, 11 and 16 were acoustically evaluated by a trained person, counting the number of insect signals. In case of strong external disturbances the section for evaluation was moved to the next 15 undisturbed seconds of the recording. Therefore, 12 periods of 15 seconds were evaluated each day and the number of signals added up to a daily activity figure with standard deviation. Tab. 1 gives an overview about the duration of both experiments and the evaluated times.

In case of very frequent insect signals (more than 2.3 signals/second) an accurate count of signals was not possible and in those cases the result was given as >35 for the 15 second section. Results that are based on at least one 15-second section with more than 35 signals are indicated in the result section.

The increase of beetle activity inside the box as indication for increasing number of insects over time was evaluated at intervals of 1-11 but mainly 3-4 days.

**Tab. 1** Overview of experimental duration and acoustically evaluated days.

	Duration of the experiment	Evaluated days
<b>1 m<sup>3</sup> box</b>	148 days $\approx$ 21 weeks	24 days (72 hours)
<b>8 m<sup>3</sup> box</b>	166 days $\approx$ 24 weeks	26 days (78 hours)

### Modelling of beetle population

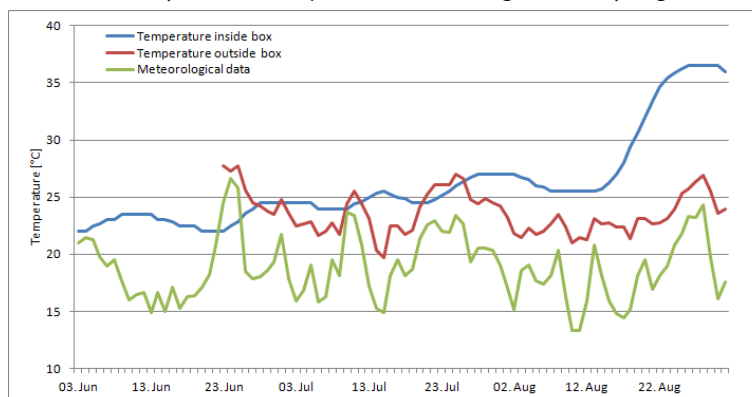
To estimate the size of the beetle population during the course of the experiment, the computer model "SITOPHEX" was used (Prozell et al., 2004). This model calculates the number of beetles and development stages over time considering temperature, relative humidity, reproduction rate and mortality rates of different stages.

## Results

### Temperature

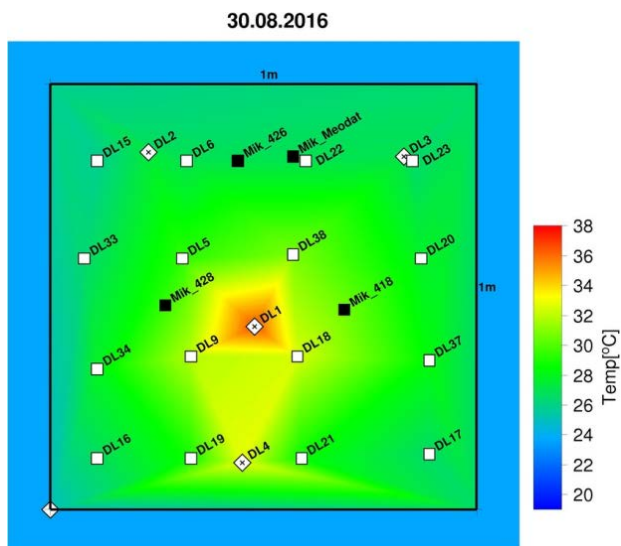
In the first weeks of the experiments the temperatures inside the boxes rose slowly depending – with some delay – on the temperatures outside the box. The temperature outside the box and inside the storehouse was largely dependent on the ambient temperature.

After 12 weeks, the temperature inside the 1 m<sup>3</sup> box just above the beetle-infestation rose quickly. During a period of 12 days, the temperature increased by 11°C, while the temperatures outside the box and the meteorological data remained at a lower level. The temperature increase inside the box was therefore not caused by external temperatures but biological activity (Fig. 2).



**Fig. 2** Daily average temperature inside the 1 m<sup>3</sup> experimental box above initial beetle infestation point compared with temperatures outside the box and data from a nearby meteorological station at about 1 km distance from the building.

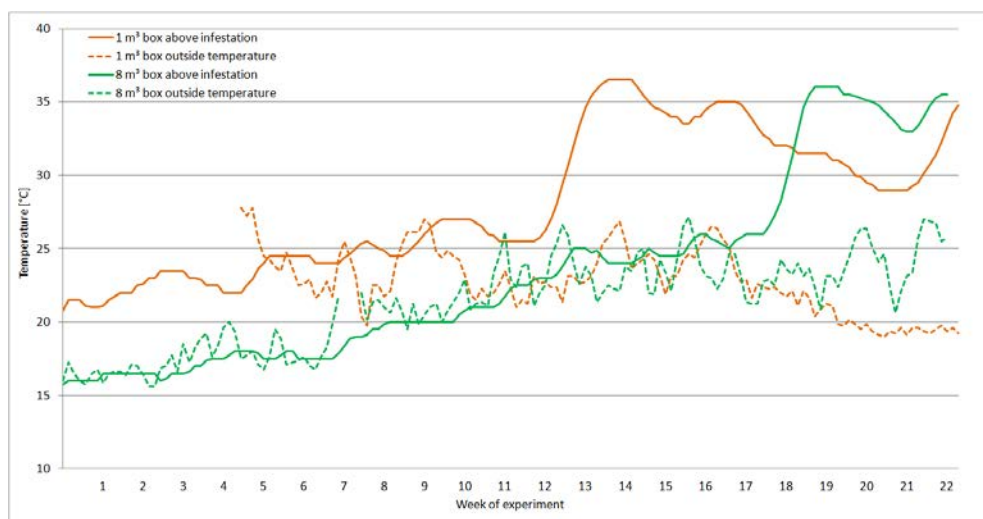
The increase of temperature was most pronounced in the area where the beetle larvae were placed at the beginning of the experiment (Fig. 3) indicating a proliferation of weevils and larvae in the area.



**Fig. 3** Temperature in and outside the 1 m<sup>3</sup> experimental box measured with 21 data loggers on the 30<sup>th</sup> of August. DL1 is the data logger just above the centre of beetle infestation.

An increase of relative humidity could be observed simultaneously with the rise of temperature. While relative humidity rose by 7 percentage points in the first 10 weeks of the experiment, it increased steeply another nearly 3 percentage points in 5 days. Afterwards the relative humidity decreased again but stayed at a higher level.

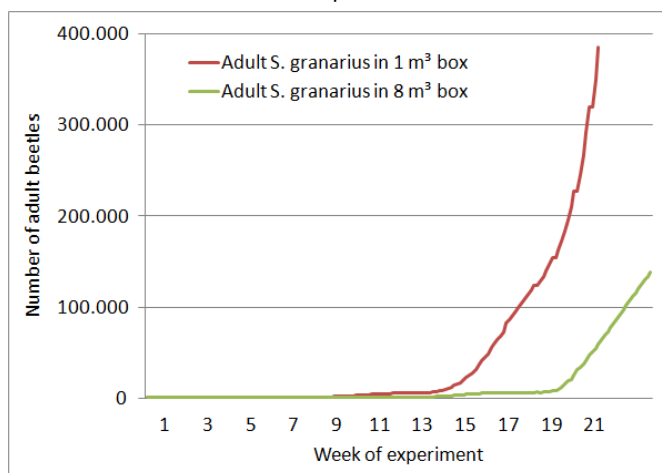
The results of the 8 m<sup>3</sup> box were comparable, but the increase of temperature started after 122 days and therefore more than 5 weeks later compared to the 1 m<sup>3</sup> box. The reason for this delay is the much lower temperature in the second experiment. While the first experiment in the 1 m<sup>3</sup> box started in May with wheat temperatures of more than 20°C in the box, the second experiment in the 8 m<sup>3</sup> box started in March during very cold weather. Start temperature of the wheat was about 16°C and it took until the middle of May before the wheat reached a comparable temperature as at the start of the first experiment. This led to delayed development of beetles and therefore a later increase of temperature as an indicator for beetle infestation (Fig. 4).



**Fig. 4** Comparison of temperature in both experiments (1 and 8 m<sup>3</sup>) over time. A temperature increase indicating insect infestation in the 1 m<sup>3</sup> box became obvious at week 12 while it took until week 18 in the 8 m<sup>3</sup> box due to lower wheat temperatures.

### Modelling of beetle population

The population size of adult *S. granarius* calculated using "SITOPHEX" showed large differences between both experiments (Fig. 5). While the population rose from 200 to nearly 400000 adults in the 1 m<sup>3</sup> box in 21 weeks, it only reached about 150000 in 24 weeks in the 8 m<sup>3</sup> box due to the lower temperatures and therefore slower insect development.



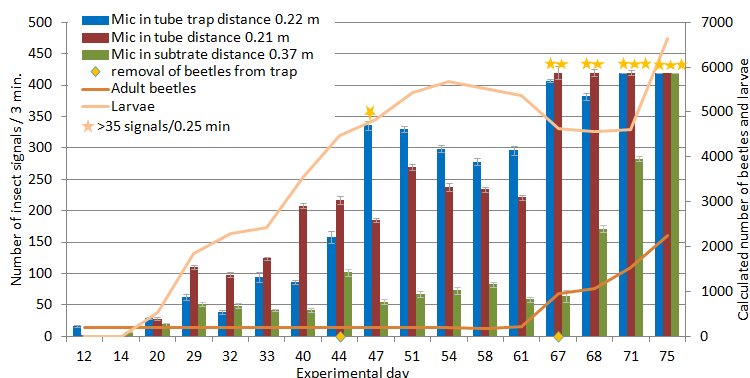
**Fig. 5** Calculated numbers of adult *Sitophilus granarius* during the course of the experiments in 1 and 8 m<sup>3</sup> wheat based on the software "SITOPHEX".

### Experiment in the 1 m<sup>3</sup> box

The evaluation of the recordings started before the first beetles were expected to hatch and ended at the end of August after the temperature increase indicated infestation. From the end of July (experimental day 69) onwards the number of signals picked up by the microphones in both metal

tubes exceeded the maximum countable number of 140 signals/minute, continuously. At the microphone placed directly into the grain, this point was reached after the 2<sup>nd</sup> of August.

Eleven days after the first beetles were expected to hatch, the first weak acoustic beetle signals could be detected with the microphone inside the tube trap at 0.22 m distance from the infestation start point while after 23 days the signals were strong and easy to detect. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the number of beetle signals during the course of the experiment from the day, when the first signals were detected, to the day, when the number of signals exceeded the maximum countable number of signals on all three microphones on the 6<sup>th</sup> of August.



**Fig. 6** Beetle signals recorded with three microphones inside the 1 m<sup>3</sup> box. The columns show the sum of signals of twelve 15-second periods during an experimental day with standard deviation. Days on which the maximum countable number of 35 signals per 15 seconds was exceeded in at least one period are marked with an asterisk. Additionally, the calculated number of larvae and adult beetles inside the experimental box and the days on which beetles were removed from the trap are given.

All microphones showed an increase of signals with time corresponding to the increasing number of beetles and larvae inside the box. Already three weeks after the beginning of the experiment and about two weeks after the first adult beetles hatched signals could be counted regularly at all microphones.

A decrease of numbers of larvae was observed between experimental day 54 and 71 which resulted from the fact that all introduced larvae had the same age. Therefore, they pupated all at about the same time which led to a decrease of larvae before the number of adults increases. Afterwards, the number of larvae increased steeply after the young larvae of the next generation started to hatch.

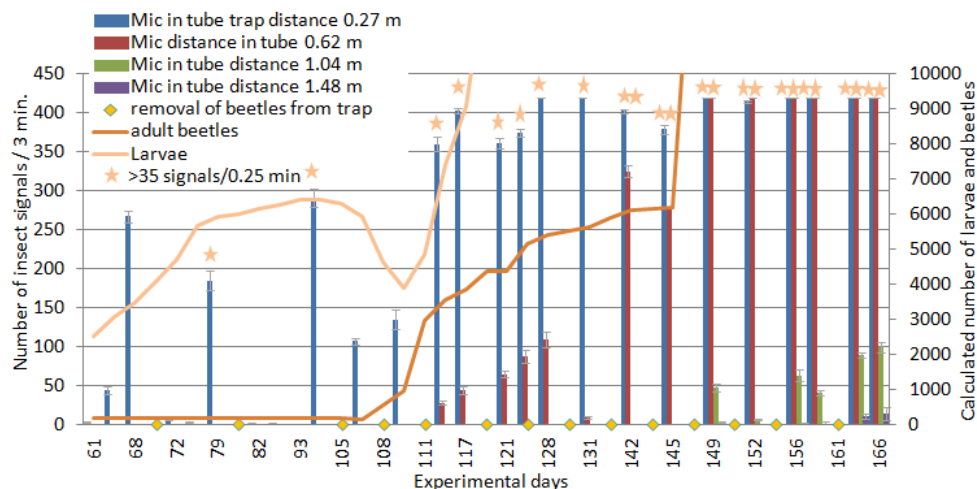
#### Experiment in the 8 m<sup>3</sup> box

First beetle signals could be detected inside the tube trap at the beginning of May more than 8 weeks after the first beetles hatched. Fig. 7 shows the number of beetle signals during the course of the experiment from the day when the first signals were detected to mid-August, when the experiment ended.

For more than 7 weeks, the microphone inside the tube trap was the only one recording signals. The high number of signals inside the tube trap was caused by few beetles inside the trap. After removal of three beetles from the trap on day 69, the number of detected signals decreased from 267 before to seven signals after removal. The next beetles were trapped in the tube causing the next peak on day 79. After the next generation of beetles hatched and the number of beetles increased inside the box, the trap-effect became negligible and the removal of beetles from the trap did not cause a clear decrease of signal numbers due to insects moving and feeding in the surrounding of the tube.

The microphone inside the tube at 0.62 m distance from the infestation recorded the first signals nearly 16 weeks after the first beetles hatched. The number of signals increased with the number of larvae and beetles in the box.

After nearly 21 weeks the first beetle signals were detected at a distance of 1.04 m, while it took only another 2 weeks until signals were recorded at 1.48 m distance from the infestation.

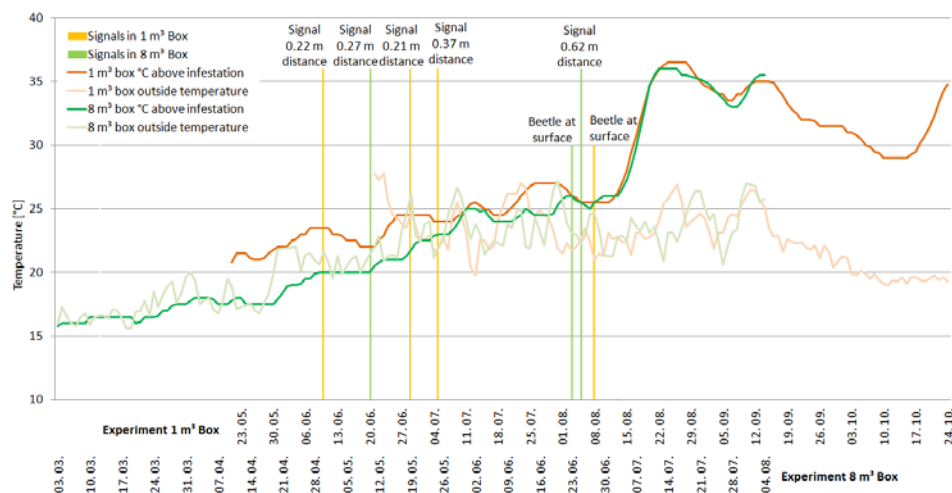


**Fig. 7** Beetle signals recorded with four microphones inside the 8 m<sup>3</sup> box. The columns show the sum of signals of twelve 15-second periods during an experimental day with standard deviation. Days on which the maximum countable number of 35 signals per 15 seconds was exceeded in at least one period are marked with an asterisk. Additionally, the calculated number of larvae and adult beetles inside the experimental box and the days on which the beetle were removed from the trap are given.

#### Comparison of temperature, insect detection and acoustic signals in both experiments

The results of both boxes are comparable apart from the fact that the development of beetle infestation was slower in the 8 m<sup>3</sup> box due to lower temperatures. Fig. 8 shows the temperature above beetle infestation in both experiments as already given in Fig. 4 but time-displaced for better comparison. The day, when first signals were detected on the different microphones is displayed in the figure, showing that in both experiments an infestation of beetles could be discovered at least 8 weeks before an increase of temperature directly above the infestation was measurable and at least 6 weeks before beetles appeared on the surface of the substrate.





**Fig. 8** Comparison of temperature in both experiments (1 and 8 m<sup>3</sup>) displayed six weeks time-displaced. Both experiments show a very similar temperature curve related to the beetle infestation. Additionally, given are the times of the first signals recorded by microphones at different distances and of the first observation of beetles at the substrate surface in both experiments.

## Discussion

Aim of the project was the development of a permanent acoustic early detection system for farmers and smaller storage keepers. The results showed that acoustic monitoring can provide much earlier detection of beetle infestation compared to conventional methods such as temperature measurements or surface traps. But it must be considered that in professionally managed storages the detection with conventional methods such as traps might be possible at an earlier stage as shown in the experiments and that in those cases the gap between acoustic and conventional detection might be smaller. But farmers and keepers of smaller storages often do not have the time for close inspections or the wheat is stored in silos that are not easy to access. In these cases, one could therefore benefit from early acoustic detection. In both tests, acoustic detection was possible many weeks before temperature rose. Of course, the distance between the initial point of infestation and the first acoustic device would determine how much earlier acoustic detection is possible in comparison to temperature probing or traps.

On the other hand, in the experiments the position of the infestation was known and the temperature measurements were taken exactly at the right position to detect an increase of temperature as quickly as possible. Under real-life conditions the temperature increase would likely be detected at a later stage due to a less perfect position of the sensor. Thus, temperature monitoring could be even slower than recorded here.

The beetles were detected at an early stage at distances of 0.22 to 0.27 m from the infestation and even at distances of 0.62 m from the infestation acoustic detection was earlier than by temperature.

During the 1 m<sup>3</sup> box experiment, the microphone inside the tube detected more signals than the one placed directly inside the wheat. This might be due to the larger surface of the tube that bundles the signals from a larger area. However, it could also be because the microphone in the tube was closer to the release point of beetles (microphone in tube 0.21 m, microphone in substrate 0.37 m). Additionally, it is not known how evenly the beetles spread from the position of the initial infestation and therefore how many beetles were close to which microphone when signals were detected. But since a microphone directly inside a stored grain mass would be very susceptible to

dust and tractive forces during grain loading and unloading, the tube would be useful to provide protection for the highly sensitive equipment and might also have acoustical advantages.

The tube trap greatly increased the detection as long as the number of beetles was small and even one beetle in the trap caused strong signals. At a later stage of infestation, the trap function was negligible, with still high numbers of signals after removal of beetles from the trap.

The calculated number of beetles for the experiments was important to get an impression about the population size and the differences between the two experiments. Since the program was not developed for experiments like the one described above, there is an important flaw. While it is possible to enter the number of beetles at the start of the experiment as a basis for the population, it is not possible to subtract the number of beetles removed from the trap. Especially in the first weeks of the experiment with only 200 adult beetles in the box, even small numbers of removed beetles will alter the size of the developing population. Therefore, the population size given in the results is likely to be overestimated.

The results indicated that the described acoustic system might be a suitable method for early detection of insects in storages. In a next step, the developed "Beetle Sound Tubes" will be installed in silos and tested with automatic signal detection software to provide farmers and storekeepers with detailed information about infestation and possible treatment.

### Acknowledgement

The project "InsectTap" was supported by funds of the Federal Ministry of Food and Agriculture (BMEL) based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food under the innovation support programme (BLE project no. 2814801311).

"Beetle Sound Tube" is an eip-agri Agriculture & Innovation project funded by the European Agricultural Fund for Rural Development (EAFRD) on behalf of and co-funded by the Ministry of Rural Development, Environment and Agriculture of the Federal State of Brandenburg (MRDEA).

Many thanks to the team of the Julius Kühn-Institute department for stored product protection for all the help with the experiments, Ralf Meyer from WEDA for the Sound Tube construction, Dietmar Roßberg for his support with "SITOPHEX" software and Holger Deckelmann for the visualization of temperature measurements.

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### Controlling insects in stored grain by disturbing the grain

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DOI 10.5073/jka.2018.463.078