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Acoustic detection and automatic identification of insect stages activity in grain bulks by noise spectra processing through classification algorithms

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Abstract

The activity of insects within a grain bulk produces noises in the audible range of wavelengths, which can be detected by high performance acoustic sensors. A portable probe of 1.4 m length was built up with three levels acoustical sensors coupled to a computer-assisted processing system. The recorded sound signals of the major grain insect species were digitized and stored into a reference database. A classification algorithm was developed for the automatic recognition of recorded insect noise signals by their comparison to the specific spectra of the reference database. The system was calibrated for *Sitophilus oryzae* and *Rhyzopertha dominica*, either at the adult or larval stage. The performances of the computer-assisted acoustic probe have been checked in small pilot scale conditions of 300-kg grain bin units. The distance to the sensor from which the insect noise spectrum was no more accurately identifiable was assessed at 20 cm, representing a "sampled volume" equivalent to 65 kg of wheat gain at each probing. For *S. oryzae* in wheat grain, the relationship between insect activity (either of larval or adult stage) and density levels was quantitatively modelled in the range from one individual per 10 kg to 10 individuals per kg at temperature levels from 5 to 30 °C. The cold stupor temperature of the rice weevil larva was assessed through the determination of the temperature level at the complete stop of activity deduced from the acoustical data. The threshold of temperature enabling insect larva activity was observed as low as 8 °C, *i.e.* much lower than was previously established, published, or believed. This new tool of early detection of an infestation in grain bulk will be now associated to decision support system for IPM implementation in grain handling and storing plants.

Key words: Insect detection, *Sitophilus oryzae*, hidden infestation, acoustical probe, classification algorithm, temperature-dependent activity.

Introduction

The presence of live insects in commercial grain lots is unacceptable in grain trade. Current Standards in international trade apply only to live external insects, which are observable visually on representative samples of grain. For a practical application of this rule in grain trade, it is generally translated into a new one: insect-free or insect absence checked on a representative sample withdrawn from the lot and examined by a Standard method (e.g. ISO 6322-3, 1989) for insect detection (more often carried out on a 1-kg sample by sieving). Such methods do not

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detect hidden infestation by pre-emergent stages of primary pest species (*Curculionidae*, *Bostrichidae*, *Gelechiidae*, and *Bruchidae* for pulse grains only) within the kernels which population density may be ten times more numerous than free-living adults (Fleurat-lessard, 1988). Consequently, the early detection of hidden insects during grain storage remains a major issue for the cereal handling and milling industry. A number of methods have been proposed for control purposes of infestation of grain lots at a commercial transaction. Among these, the acoustical detection of insect noise has been investigated for more than 20 years with more or less success in the development of devices or tools for the detection of hidden insect infestation within grain samples or even directly in grain bulks (Fleurat-Lessard and Andrieu, 1986; Hagstrum et al., 1990; Hagstrum and Flinn, 1993; Fleurat-Lessard et al., 1994; Hagstrum et al., 1996). One of the major drawbacks of the acoustical probes designed for insect populations monitoring in grain bulks was the low sensitivity of the first acoustic systems conceived during the last decade, which enable to only detect population densities higher than 1 insect per kg of grain that is a comparable limit of the classical control of insect infestation by sieving a grain samples (Hagstrum et al., 1990; Litzkow et al., 1990; Shuman et al., 1993; Hagstrum et al., 1996; Shuman et al., 1997). These first studies did not allow the crossing of this technical barrier of the lowest level of population detectable density in a 1-kg grain sample: the minimum detectable density is one insect per kg.

In order to lower this threshold of detectable insect population density, it was suggested three new approaches by which the potential of acoustic technology could be largely improved. First, different stored-grain insect species having different behaviour, the identification of sound signature of each species and active stage may enable a more easy separation of insect sound spectrum signature from background noise (Andrieu and Fleurat-Lessard, 1990; Fleurat-Lessard et al., 1994; Weaver et al., 1997). Second, the modern computer and electronic technology now available enables the processing of acoustic signatures into numeric data suitable for an automatic recognition of insect sound spectrum and an easy discrimination from the noises in the storage environment or from the grain handling machinery (Schwab and Degoul, 2005). Third, instead to focus the detection of an infestation at a grain inspection point at a commercial transaction, the monitoring of insect presence in stored grain bulks should be preferred. In carrying out the detection in the open space of a grain bulk and in choosing the locations where conditions for insect multiplication and aggregation are the most favourable, the minimum level of detectable density can be greatly reduced. Thus, the insuperable threshold of one insect per kg, when the detection is carried out on a sample, does not exist anymore in these “open field” conditions (Rodriguez Gobernado et al., 2005).

The first aim of our work was to define the performances and to test the operational version of a fully automatic system for the surveillance of insect presence in grain bulks (in a lorry, in a bin or in a large bulk) with three main goals: i/ the assessment of the mass of grain in which the detection of a single individual is possible; ii/ the potential of the signal processing system to differentiate between species and stages sound spectra; iii/ the design of the models for linking stored-grain temperature and the size of insect population to the sound numbers emission of the nibbling hidden stages. These models are indispensable for the coupling of this new tool for monitoring low-density-level insect infestation in grain bulks with the PC-assisted decision support system for stored-grain overall quality management (Ndiaye, 2001; Ndiaye et al., 2002).

Materials and methods

Acoustic equipment design

The acoustic detectors were piezoelectric sensors (such as piezoelectric ceramics found in portable phones) fixed per pair at three levels of

a metallic cylindrical probe of 1.4 m long and 50 mm in diameter. The upper head of the probe contains an electronic system connected to the sensors and ensuring the acquisition and the processing of the sound-spectrum data from the acoustic transducers and the computing of the data from the other sensors. At the lower tip of the probe tube is a conic end facilitating the penetration into the grain mass and in which are inserted a temperature gauge and a moisture meter.

The sound signal transmitted by each sensor is directly pre-amplified by an electronic amplifier housed in the tube of the shaft behind each sensor level. Then, the analogic signal is transmitted to the processing unit at the head of the shaft (Figure 1).

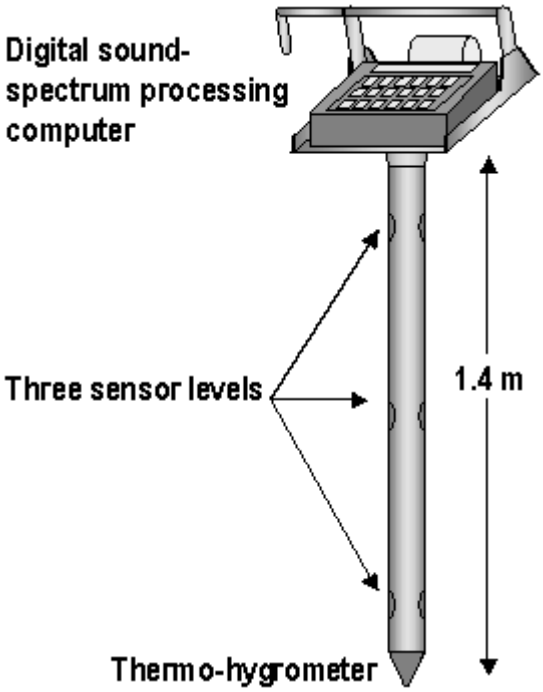

Figure 1. Schematic representation of the portable acoustical probe "Early Warning Detector (EWD™)" designed for the monitoring of insect primary infestation in grain bulks.

The electronic system incorporates an autonomous rechargeable electric power supply unit with 12 h autonomy enabling the use of the acoustic probe on a whole day of work.

The electronic module was conceived i/ to acquire the sound signals from each level of piezoelectric sensors during a unit of measurement time (generally fixed at 2 min); ii/ to process the analogical signal into a numeric one enabling either the storage of reference spectra into a database of identified spectra, or the comparison of each acquired acoustical signal to the reference spectra of the database; iii/ to compute all the inputs from the sensors and the outputs from the processing in order to print on a ticket the presence, and if any, the identification of the main species and the corresponding infestation risk level. The computer-like processing module inside the electronic system consists in three main parts: i/ The analogical to digital conversion board; ii/ the processing board which detects the transient noises coming from the sensors, process each spectrum for the comparison to the insect sound spectrum referenced in the database; iii/ the display of all results on a graphical user interface under the form of infestation risk diagnosis and alarm message when the adjustable threshold of risk is reached or overcome. The reference database was fed with hundreds of standardized sound spectra per case study. The case studies were the different combinations of the triple association: development stage (adult or larva) / insect species / grain type.

Procedure of classification of acoustic sound spectra

The reference spectra database was built from the most characteristic spectra of the insect activity in grain. For the adult stage, the activity can be moving among the kernels or nibbling the kernel from outside. For hidden stages, the activity is only nibbling the kernel endosperm from the inside. The main criteria chosen for the differentiation were: i/ the redundancy of similar-shaped signals during the same sequence of recording; ii/ the similarity of the signal spectra in a comparison from each to another. Thus, the same species at the adult stage is referenced in the database with two types of reference

spectrum, one corresponding to a moving activity and another to the feeding activity. The spectra in each situation are tested for similarity and all the spectra with less than 10 % dissimilarity are stored in the reference database. A total of 990 spectra were sampled in controlled conditions of a small grain container. The sound spectra were processed for the extraction of a specific shape for each case study. Among these, only the spectra with more than 90 % similarity were finally introduced into the database. The comparison of the shape and the range of wavelength with the maximum energy between two different case studies were carried out in order to differentiate between species and stages in the same probing. For the use of a classification algorithm, some pertinent parameters of the standardized sound spectra were extracted: i/ the energy aspect (signal to noise ratio); ii/ the frequency aspect (position of the peaks of energy on the frequency range of the whole spectrum). A set of parameters related to these two factors for differentiation were constituted to be used by the classifier as reference patterns for the automatic recognition of the species, the stage and the size of the population at the probing location.

The classification was carried out in several steps for the discrimination of stage, species and assessment of the level of risk (Figure 2).

Relating the sound frequency to the population size (assessment of population density)

An experimental study was performed to assess the density of infestation as a function of the insect species (adult and hidden stages separately), the temperature and the number of recognized sounds per unit of time (2-min scanning time). The first experiment was performed with *Sitophilus oryzae* (L.) infested kernels by mixed-aged larvae (X-rays detected

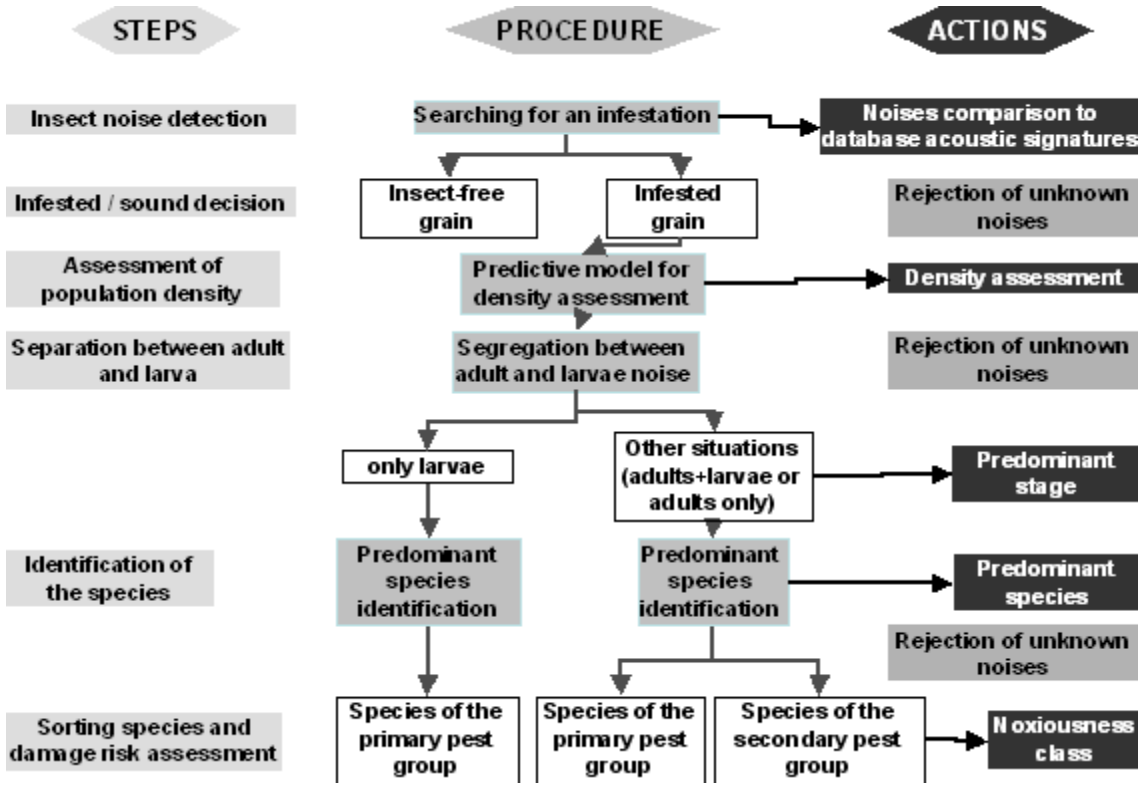

Figure 2. Automatic classification of insect noise spectra recorded from a grain bulk in view of an identification of insect species and stage generating the sounds performed by the acoustical probe EWD™.

and controlled for their nibbling activity) taken as a model. The wheat batches at 12.5 % moisture content (m.c.) were stored in small bins of 300 kg capacity. They were infested with different insect densities (from 1 individual per 10 kg to 10 individuals per kg) during the bin loading. The EWDä system was used in conditions similar to a practical utilisation in a grain bulk for the quantification of recognized insect sounds per 2-min time scanning periods. The limit of detection was observed at a distance of about 20 cm in front of the sensors. Thus, the volume of detection of the EWDä acoustic probe was limited by a central cylinder of 20 cm in diameter, i.e. a prospected mass of 65 kg of wheat at 12.5% m.c. (Figure 3). The experimental bins were stored in an air-conditioned room in constant conditions of 25 °C and 70 % relative humidity. The measurement of insect sounds per 2-min scanning time were repeated at least 10 times per case study (hidden stages density). The mean number of recognized insect sounds per period of acoustical scanning (2 min) was correlated with the density of insect per kg of wheat.

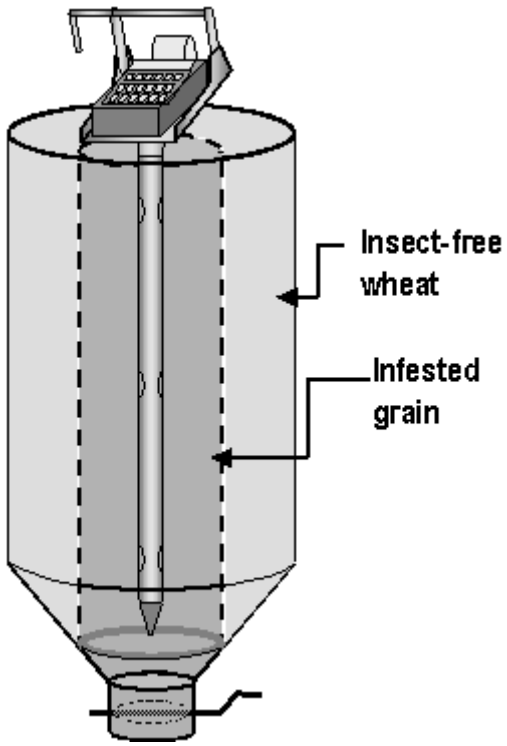

Figure 3. Experimental design for the modelling of the relation between insect sounds frequency and density of *S. oryzae* population in the grain mass prospected with the EWD™ acoustic equipment.

Influence of temperature on the level of recordable sounds frequency along time

The experiment was conducted in an air-conditioned room where temperature level can be fixed at different levels in the range from 5 to 30 °C. The EWD equipment was partially introduced up to half of its length into a batch of grain stored in a sound-insulated container loaded with 8 kg of wheat grain (Figure 4). Ten kernels internally infested by active larvae were introduced in the grain batch at a low distance of

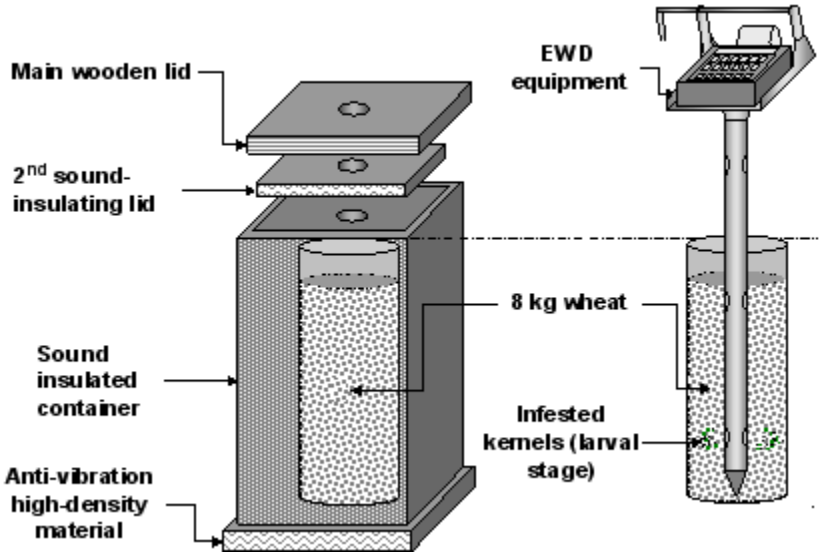

Figure 4. Experimental design for the study of the correlation between acoustic sounds emission by *S. oryzae* larvae and grain temperature level.

the position of the first level sensor. The temperature of the room was regularly changed day after day in order to smoothly move from unfavourable low temperature levels to favourable temperature levels for insect larva activity. The temperature inside the container at the point of introduction of infested grains was recorded at four min intervals by calibrated thermocouples. The frequency of recognized sounds emitted by the active larvae was checked through the EWDä acoustic equipment maintained in the grain batch. The relation between the number of sounds recorded per 2-min scanning periods and the temperature level was established.

Results

Differentiation between sound spectra of different species or stages

For the adult stage of *S. oryzae*, it was regularly observed a major peak of energy in the frequency spectrum, moving in a frequency range from 1.8 to 3.0 kHz, with a small resumption peak in the range 3.3 - 3.8 kHz. For the larval stage, the peak of energy for a majority of the recordings was observed in a narrow frequency range from 1.3 up to 2.0 kHz (Figure 5). Since the larval activity is mainly feeding, the lower range of acoustical signal peak energy may likely be related to the activity of feeding either at the adult or the larval stage (mandible nibbling sound). For the adult stage of *Rhyzopertha dominica* (F.), it was observed two peaks of energy in the frequency spectrum in the range of 1.5 to 2.5 kHz and 2.6 to 3.2 kHz. The first peak at the lower frequency may again be related to feeding activity by analogy with the larva spectrum for which only a single peak was observed in the frequency range 1.7 to 2.5 kHz. The analysis of the signatures of these two major species were found with significant differences at the adult stage enabling an automatic identification of the infesting species but the differentiation was not possible with the larvae spectra. However, the difference between larval and adult spectrum, whatever the infesting species, could be easily separated by the automatic classification algorithm.

Relation between population density and the frequency of emitted sounds

Grain infestation by the adult stage was easily detectable with the EWD™ equipment used in the small bins (Figure 3). With the primary pest species

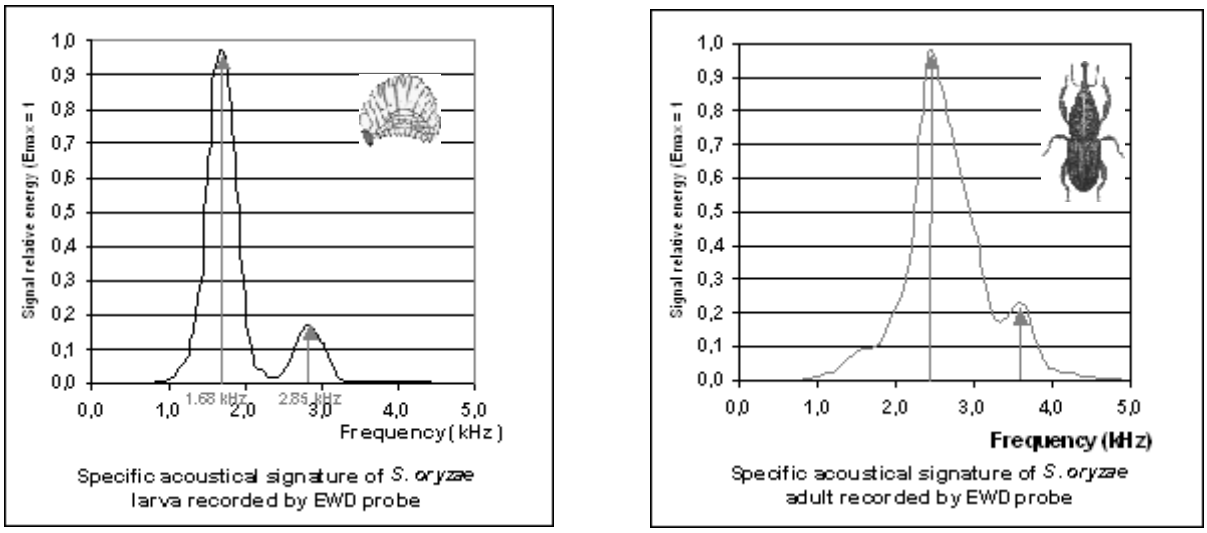

Figure 5. Specific sound spectra of *S. oryzae* larva (left) and adult (right) in wheat after the processing of specific sound signals (averaged) acquired through EWD™ acoustic probing.

S. oryzae, a density of one adult per 10 kg of wheat was detectable and identified as an adult of the primary pest group down to a temperature threshold of 15 °C with more than 95 % of likelihood. At 10 °C, this probability of detection fell down to 50 % (Figure 6). With the larval stage nibbling inside the kernels, the limit of detection with 95 % likelihood at a temperature above 14 °C was observed at one active larva per kg of wheat (Figure 7).

Relation between the level of activity and temperature

The influence of the temperature on the level of activity of hidden stages of the rice weevil could be modelled by a linear regression of the number of sounds per 2-min recording period (Figure 8). However, the correlation coefficient is low because the very high amplitude of the fluctuations in the intensity of the nibbling activity of the larvae, closely depending on the development stage they are at the time of probing. Additionally, the moulting larvae do not produce sounds during several hours and short periods of rest have been observed among active larvae along the day. The theoretical extinction of the activity determined from the regression line was observed at 8.5 °C. However, it was also stated that the larvae cannot be easily detected with the acoustical system below 10 °C. The validation of this low thermal threshold for larval activity of the rice weevil was undertaken in the last experiment conducted in the same conditions but in inducing slow changes in temperature level of the grain either towards low temperature or towards higher temperature.

Detection of the lower temperature threshold for *S. oryzae* larva activity

The decrease of temperature below the threshold of 9 °C induced the lack of positive records by the EWD™ acoustic-probe (Figure 9). The activity is again recordable when temperature is crossing the threshold of 14 °C. When the temperature decrease slope is slow (as it may be the case in large grain bulks), the extinction of nibbling activity was observed only after five days spent at 8°C. During this period spent at 8 °C, some positive records were observed that indicated that *S. oryzae* larvae are not totally quiescent at this low level of temperature (far below the theoretical thermal low limit for the development mostly described in the scientific literature around 13 °C.

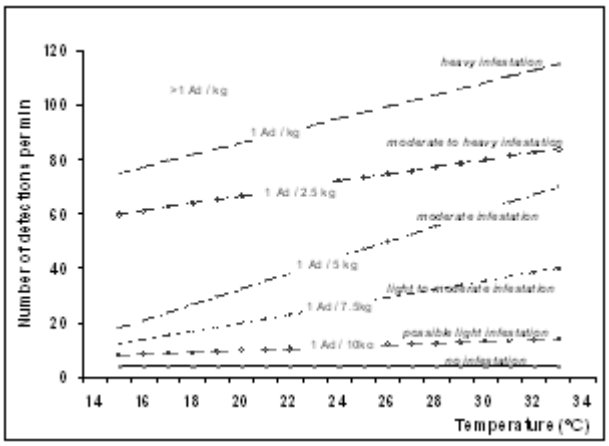

Figure 6. Relation between the population density of *S. oryzae* adults in wheat and the frequency of sound signal per min of scanning with EWD™ equipment.

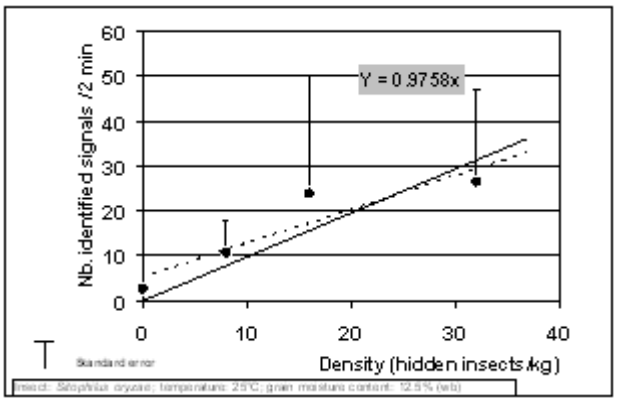

Figure 7. Modelling the relation between the population density of *S. oryzae* larva in wheat and the frequency of sounds per 2-min sequences of EWD™ acoustic-probe recording.

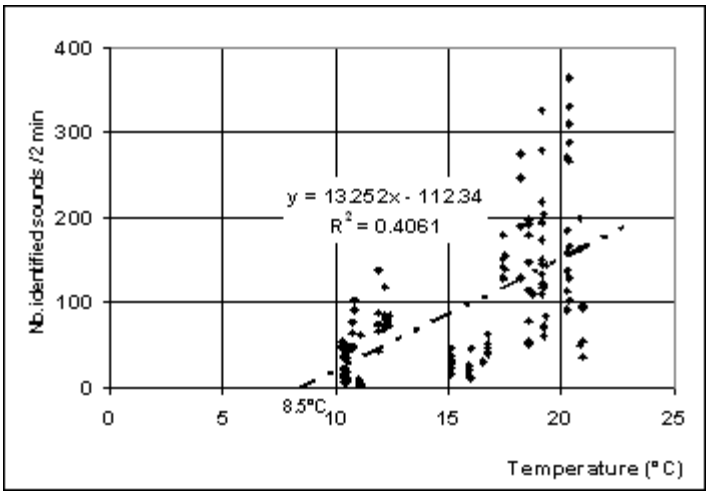

Figure 8. Relationships between grain temperature and activity level of *S. oryzae* larvae recorded by the EWD™ acoustic probe

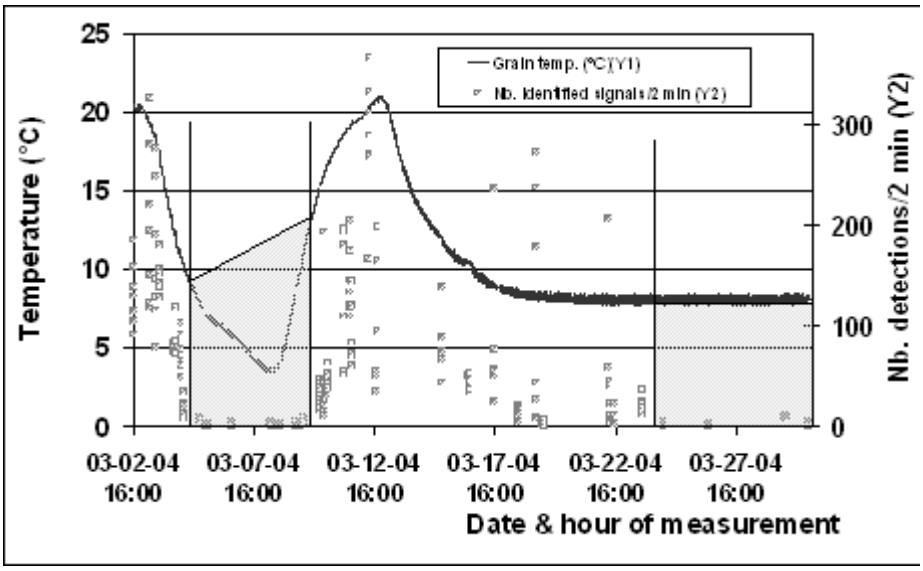

Figure 9. Sound numbers per two-min recorded by EWD™ acoustic probe for *S. oryzae* larva nibbling activity inside kernels of wheat.

Discussion

The distance of detection from the acoustic sensors up to which the identification of the acoustical signature of an insect is possible is dependant of the stage. The adult stage signature of the rice weevil is identifiable up to 20 cm in front of the sensors and is reduced when the incidence angle to the sensitive surface of the sensor is increasing. With the larvae, this distance is reduced to 15 cm and is also sensible to the incidence angle with the sensor. The volume of grain in which the detection and the identification of a single adult activity with a probability not less than 95 % was assessed to about 20 dm^3 scattered around the sensitive surface of the sensors. For wheat this "acoustic-probe prospected volume" represents more than 10 kg of grain. For the rice weevil larvae, this volume is reduced to the half and the detection of one larva is possible at the same level of probability only in 2.5 kg of wheat. Thus, the "open space"

monitoring of insect presence in stored grain bulks by the EWDä acoustic probe is greatly reducing the limit of detection of a low density infestation by primary insect pests of stored grain. Additionally, the number of probing points with this kind of tool is only limited by the available working time of the operator. Each probing operation may last five to eight min including the 2-min still recording period for acoustic sounds acquisition.

The identification of the species and stage of insect emitting the recording sounds is performed with an algorithm having three levels of rejection of unknown sounds that eliminates all unrecognised sound spectrum that differ significantly from the typical reference spectra stored in the database. This approach is reducing the risk of a false positive detection near to zero. Per counterpart, each variable requires to pool a great number of recordings in controlled conditions for feeding the database with reference sound spectra covering all the cases: different insect species at the two active stages; infesting each type grain for which the acoustic probe may be used.

The influence of the density on the frequency of recorded sounds was foreseeable and the correlation may be established again for the different main cases of noxiousness groups: adults of primary pest species; larvae of the same species; adults of the secondary insect pest species (e.g. *Oryzaephilus surinamensis* (L.), *Tribolium castaneum* (Herbst), *Cryptolestes ferrugineus* (Stephens)).

The most important model is the correlation between temperature and frequency of sounds per unit of recording time. The use of this insect detection device as a decision support is possible to advise the stock owner about the optimal storage strategy. Nevertheless, the limitation of the impact of a starting infestation just detected with the EWDä probe would be possible only if a predictive model of population dynamics of the discovered species is available for the prediction of the safe storage period before this infestation becomes detectable by conventional methods. This huge task of modelling was undertaken only recently for the grain weevils that are considered in France as the major cereal grain pest species during storage.

Conclusion

Today, the surveillance of deterioration factors of grain is a requirement of the new Quality Assurance regulations generalized to the whole chain of grain derived products, from the field to the finished food product (Anonymous, 2004). These regulations are explicitly based on the HACCP system application. In the HACCP approach, the monitoring of "biological hazards" that may endanger the sanitary and safety of stored grain bulks is required. For the prevention of stored-grain insect infestation, this monitoring consists in the early detection of the presence of noxious insect species. Monitoring is also enabling whether a control measure is being implemented and affording the expected efficacy. Deviation from a critical limit should be detected in as short time as possible and at the lowest level of risk as possible to allow the required delay of time for corrective action implementation in order to prevent a financial loss.

With the new tool of acoustical detection EWDä, identification and quantification at a very low density level of insect population in stored-grain bulks (the major issue of insect presence at grain lots transactions) may be overcome by continuous surveillance of the presence of an infestation during the entire storage period. The automatic recognition of sound signature of the hidden stages associated to the computing of population density changing in time, taking into account the grain condition, paves the way for the prevision of the safe storage period before an infestation can be detected on a delivery by an official control method. Thus, the outputs of the acoustical detection device can be used for decision support about insect risk for the quality manager. The forecasting of the safe storage period after a first detection of the presence of live insects in a grain bulk at a low density level, should facilitate the application of appropriate corrective measures or the decision to purchase the lot before the latent infestation becomes detectable.

With such a new PC-assisted insect detection probe, the preventive monitoring of live insect presence is now possible. This preventative approach is in full agreement with the application of the HACCP preventative quality assurance system in grain handling and storing plants (Fleurat-Lessard, 2006). The coupling of acoustic probe to a PC-Assisted decision support system that have been developed recently in major grain-producing countries for insect infestation forecasting or prevention (Flinn and Hagstrum, 1990; Longstaff, 1999; Mann et al., 1997; Knight et al., 1999; Ndiaye, 2001) should be the next step.

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