Available online at www.sciencedirect.com
ScienceDirect
Journal of Stored Products Research 44 (2008) 186–192
Journal of STORED PRODUCTS RESEARCH
www.elsevier.com/locate/jspr

Thermal imaging to detect infestation by *Cryptolestes ferrugineus* inside wheat kernels

A. Manickavasagan[a], D.S. Jayas[b,*], N.D.G. White[c]

[a]*Department of Biosystems Engineering, The Canadian Wheat Board Centre for Grain Storage Research, University of Manitoba, Winnipeg, MB, Canada R3T 5V6*
[b]*Department of Biosystems Engineering, University of Manitoba, 207 Administration Building, Winnipeg, MB, Canada R3T 2N2*
[c]*Cereal Research Centre, Agriculture and Agri-Food Canada, Winnipeg, MB, Canada R3T 2M9*

Accepted 12 October 2007

Abstract

Canada's zero tolerance for live insects in grain received from farmers, and shipped to domestic and export buyers, has necessitated the development of an accurate insect detection method. An infrared thermal imaging system was developed to detect infestation by six developmental stages (four larval instars, pupae and adults) of *Cryptolestes ferrugineus* under the seed coat on the germ of the wheat kernels. The artificially infested wheat kernels were removed from the incubation room (30 °C), refrigerated (5 °C) for 60 s, maintained at ambient conditions for 20 s, and imaged using a thermal camera to identify each developmental stage ($n = 283$). The means of the highest 5% and 10% of all temperature values on the surface of the grain were significantly higher ($\alpha = 0.05$) for grains having young larvae inside and lower for grains having pupae inside. Temperature distribution on the surface of the infested kernels with different stages of *C. ferrugineus* was highly correlated with the respiration rate of each developmental stage ($r = 0.83$–0.91). The overall classification accuracy for a quadratic function was 83.5% and 77.7% for infested and sound kernels, respectively, and for a linear function, it was 77.6% and 83.0% for infested and sound kernels, respectively, in pairwise discriminations. Thermal imaging has the potential to identify whether the grain is infested or not, but is less effective in identifying which developmental stage is present.

Keywords: Thermal imaging; Insect detection; *Cryptolestes ferrugineus*; Heat production by respiration

1. Introduction

Canada produces an average of 25 Mt of wheat every year, which is 49% of the nation's total grain production, and about 74% of the wheat produced is exported. *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae), the rusty grain beetle, is the most common and serious insect pest of stored grain in western Canada (White et al., 1995; Agriculture and Agri-Food Canada, 2002). The adults of this species, when acclimatized, can withstand −10 °C for several weeks (White et al., 1995). In some storage seasons, the infestation by this species is severe in Canada. For example, during 1983, upto 45% of farm granaries in Manitoba were infested by *C. ferrugineus* (Agriculture and Agri-Food Canada, 2002). If the grain is infested with one or more detectable live stored-product insects, then it is not allowed to enter the Canadian grain-handling system. The "Berlese funnel" method is commonly used in Canadian grain-handling facilities to detect the insect infestation (Canadian Grain Commission, 2004) where 1 kg of grain is placed under a heat source for 6 h. This approach takes a long time to extract the insects from a grain sample and the accuracy of this method is low for the developing life stages. Smith (1977) reported that a Berlese funnel recovered 3.4–35% of first- and second-instar larvae (free living), 52.5–85% of fourth-instar larvae (free living), and 31.2–90% of adult *C. ferrugineus*. Minkevich et al. (2002) determined that the extraction efficiencies of the Berlese funnel were 34–44% for implanted larvae, 66–86% for free living larvae and 96% for adults of *C. ferrugineus*. Furthermore, it is not possible

*Corresponding author. Tel.: +1 204 474 6915; fax: +1 204 474 7568.
E-mail address: Digvir_Jayas@umanitoba.ca (D.S. Jayas).

0022-474X/$ - see front matter
doi:10.1016/j.jspr.2007.10.006

to extract pupae by the Berlese funnel method, as there is no movement at this stage.

The International Standards Organization has standardized five methods to determine the hidden insect infestations in cereals and pulses: (i) determination of carbon dioxide production method, (ii) ninhydrin reaction with amino acids, (iii) whole grain flotation method, (iv) the acoustic method, and (v) the X-ray method (ISO 6639-4, 1987). In the first method, the amount of carbon dioxide generated from the bulk sample during 24 h incubation is measured and the degree of infestation is determined. This method is not suitable for high moisture grains (above 15%) as the carbon dioxide produced by the grain and any microorganisms present interferes with the results.

In the second method, the grain sample is crushed, and amino acids from any insects present react with ninhydrin-coated paper to give a purple stain related to the level of infestation. The principle of the next method (whole grain flotation) is that internal grain feeders reduce the mass of the grain to the extent that infested grains float. It is not a suitable method for infestations of *Cryptolestes* spp.

The acoustic method relies on detecting the sound generated by the movement and feeding of insect developmental stages. The grain sample is placed inside a soundproof box that is connected to an amplification system that transmits noise from the feeding activity of insects. The recent developments in acoustic sensors have enabled this method to detect larval stages (Fleurat-Lessard et al., 2006), assess population density (Shuman et al., 1993, 1997), and in some cases to identify insect species (Hagstrum and Flinn, 1993). However, this method cannot detect non-feeding stages (eggs and pupae) of the insect.

For the X-ray method, the grain is exposed to soft X-rays, and the inspection of the X-ray images reveals the presence of hidden infestation that has progressed beyond the egg or early larval stage.

The use of thermal imaging offers another approach to detect all post-embryonic stages of an infestation. The respiration of insects (at all life stages) and resulting heat production are higher than that of the grain (Cofie-Agblor et al., 1995a,b, 1996a,b; Damcevski et al., 1998; Emekci et al., 2002, 2004). The heat production by respiration of any grain is around 0.01 W/t (Muir, 1997). The heat production of adults by respiration in 10 h was 66–81 μW per insect for the granary weevil, *Sitophilus granarius* (L.) (Coleoptera: Curculionidae), 46–56 μW per insect for the rice weevil, *S. oryzae* (L.), 18–40 μW per insect for the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), and 13–35 μW per insect for the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) (Cofie-Agblor et al., 1995b). Therefore, while mapping the surface temperature of the grain, the hidden infestation inside a kernel may be detected. The objective of this research was to determine the efficiency of a thermal imaging technique to detect the presence of *C. ferrugineus* inside wheat kernels at six developmental stages (four larval instars, pupae and adults).

1.1. Thermal imaging

Thermal imaging is a technique to convert the invisible radiation pattern (temperature) of an object into a visible image. By this method, the surface temperature of any object can be mapped at a high resolution in two dimensions. These thermal data may be used directly or indirectly in many ways. Thermal imaging has been used by many researchers for applications in agriculture such as the determination of plant physiological state, irrigation scheduling (Jones, 1999), yield forecasting (Smith et al., 1985; Stajnko et al., 2004), maturity evaluation of fruits (Danno et al., 1980), detection of bruises in fruits (Danno et al., 1978; Varith et al., 2003), and detection of spoilage by microbial activity (Hellebrand et al., 2002). However, there is little application of this technology in grain storage.

2. Materials and methods

2.1. Insect culture

The procedure described by Karunakaran et al. (2004) was followed for the development of *C. ferrugineus* cultures and artificial infestation of wheat grains. Canada western red spring (CWRS) wheat was conditioned to 14% moisture content (wet basis) and 400 kernels were artificially infested with *C. ferrugineus* eggs and incubated at 30 °C and 70% relative humidity (r.h.). The kernels were thermally imaged on days 4, 8, 11, 15, 22, and 27 to represent the infestation by four larval (L_1, L_2, L_3, L_4), pupal and adult stages, respectively.

2.2. Image acquisition

For each life stage, the kernel was moved from a 30 °C incubator to a refrigerator (5 ± 2 °C) for 60 s and then to ambient conditions for 20 s, before being thermally imaged. This pretreatment was given to the kernels to magnify the difference in the temperature profile of infested and uninfested grains (times were selected based on preliminary trials).

After imaging, the kernel was transferred back to the incubator. The control samples (uninfested wheat) were also placed in the same environment as the infested grains and thermally imaged similarly. An un-cooled focal plane array (contained a two-dimensional matrix of detector elements, typically at the focal plane) type infrared thermal camera was used in this study (Model: ThermaCAM™ SC500, FLIR systems, Burlington, Ontario, Canada). A 50 μm close-up lens was attached to the original lens of the camera (FOV 24 × 18°) to obtain the magnified thermal image of a kernel. The thermal resolution of the camera was 0.07 °C at 30 °C.

2.3. Data analysis

Algorithms were developed in Matlab software (Version 7.1, The Mathworks Inc., Natick, MA) to segment the kernel