

散装花生和玉米中谷斑皮蠹和花斑皮蠹的声音识别方法^{*}

常菲菲^{1,2**} 杨晓军¹ 鲁玉杰^{2,3} 郑斯竹^{1***} 苗世远³ 娄定风⁴

(1. 南京海关动植物与食品检测中心, 南京 210001; 2. 河南工业大学粮食和物资储备学院, 郑州 450001;
3. 江苏科技大学粮食学院, 镇江 212000; 4. 深圳海关动植物检验检疫技术中心, 深圳 518045)

摘要【目的】 对谷斑皮蠹 *Trogoderma granarium* 和花斑皮蠹 *Trogoderma variable* 成、幼虫取食花生和玉米的声音进行参数分析, 以通过声学方法实现 2 种皮蠹种类和虫态的鉴定。**【方法】** 采用声学软件 Cool Edit PRO 对 2 种皮蠹成、幼虫取食花生和玉米的声音进行时频域分析, 统计时频域上的特征声音参数虫声峰值、脉冲数及频率峰值并进行统计分析。**【结果】** 取食花生时的声音参数分析, 成虫对比: 谷斑皮蠹与花斑皮蠹成虫在虫声峰值上存在显著差异 ($P<0.05$)。幼虫对比: 谷斑皮蠹与花斑皮蠹幼虫在脉冲数上存在显著差异 ($P<0.05$)。成虫与幼虫对比: 谷斑皮蠹和花斑皮蠹的成虫与其幼虫之间在虫声峰值和脉冲数上均表现出显著差异 ($P<0.05$)。取食玉米时的声音参数分析, 成虫对比: 谷斑皮蠹与花斑皮蠹成虫在虫声峰值和频率峰值上存在显著差异 ($P<0.05$)。幼虫对比: 谷斑皮蠹与花斑皮蠹幼虫在脉冲数上存在显著差异 ($P<0.05$)。成虫与幼虫对比: 谷斑皮蠹和花斑皮蠹的成虫与其幼虫在虫声峰值和脉冲数上存在显著差异 ($P<0.05$)。**【结论】** 在 2 种皮蠹取食花生的声音中, 谷斑皮蠹成虫的虫声峰值[(-11.33±0.69) dB]>花斑皮蠹成虫[(-13.37±1.06) dB], 谷斑皮蠹幼虫的脉冲数[(21.40±3.37)个]<花斑皮蠹幼虫[(27.40±1.63)个], 谷斑皮蠹成虫的虫声峰值和脉冲数[(5.60±0.60)个]<幼虫的虫声峰值[(-6.85±0.51) dB]和脉冲数, 花斑皮蠹成虫的虫声峰值和脉冲数[(2.20±0.59)个]<幼虫的虫声峰值[(-4.96±0.39) dB]和脉冲数, 说明通过虫声峰值或脉冲数可以区分 2 种皮蠹的种类和虫态。在取食玉米的声音中, 谷斑皮蠹成虫的虫声峰值[(-23.44±1.80) dB]和频率峰值[(4451.50±165.34) Hz]<花斑皮蠹成虫的虫声峰值[(-18.02±0.70) dB]和频率峰值[(4857.50±176.36) Hz], 谷斑皮蠹幼虫的脉冲数[(16.20±1.16)个]<花斑皮蠹幼虫[(23.60±2.41)个], 谷斑皮蠹成虫的虫声峰值和脉冲数[(1.75±0.19)个]<幼虫的虫声峰值[(-7.68±0.65) dB]和脉冲数, 花斑皮蠹成虫的虫声峰值和脉冲数[(1.60±0.65)个]<幼虫的虫声峰值[(-7.24±0.66) dB]和脉冲数, 说明通过虫声峰值和脉冲数可以区分 2 种皮蠹的种类和虫态, 通过频率峰值可以完成 2 种皮蠹成虫种类的区分。

关键词 谷斑皮蠹; 花斑皮蠹; 生物声学; 虫声峰值; 脉冲数; 频率峰值

Bioacoustic detection of *Trogoderma granarium* and *Trogoderma variable* in bulk stored peanut and corn

CHANG Fei-Fei^{1,2**} YANG Xiao-Jun¹ LU Yu-Jie^{2,3} ZHENG Si-Zhu^{1***}
MIAO Shi-Yuan³ LOU Ding-Feng⁴

(1. Animal, Plant and Food Inspection Center, Nanjing Customs, Nanjing 210001, China;
2. School of Food and Strategic Reserves, Henan University of Technology, Zhengzhou 450001, China;
3. School of Grain Science and Technology, Jiangsu University of Science and Technology, Zhenjiang 212000, China;
4. Shenzhen Customs Animal and Plant Inspection and Quarantine Technology Center, Shenzhen 518045, China)

Abstract [Aim] The bioacoustic parameters of adults and larvae of *Trogoderma granarium* and *Trogoderma variable*

*资助项目 Supported projects: 国家重点专项 (2022YFC2601501); 海关总署科研项目 (2023HK52)

**第一作者 First author, E-mail: cff20000908@163.com

***通讯作者 Corresponding author, E-mail: zhengsizhu@126.com

收稿日期 Received: 2024-06-27; 接受日期 Accepted: 2024-11-02

feeding on peanuts and corn were analyzed to develop a way of using acoustic methods to identify the species and developmental stage of these pests in bulk stored peanuts and corn. [Methods] The acoustic software Cool Edit PRO was used to perform time-frequency domain analysis on the sounds produced by adults and larvae of two species while feeding on peanuts and corn. Statistical analysis was performed on characteristic acoustic parameters of insect sounds in the time-frequency domain, including the peak sounds, number of pulses, and the peak frequencies, to determine key identifying features. [Results] There were significant differences in the peak sounds of adult of *T. granarium* and *T. variabile* ($P<0.05$). Significant differences in the number of pulses produced by the larvae of *T. granarium* and *T. variabile* ($P<0.05$). Significant differences between adults and larvae in sound peak and number of pulses ($P<0.05$). When feeding on corn, there were significant differences in the peak sounds and peak frequencies of adult of *T. granarium* and *T. variabile* ($P<0.05$). Significant differences in the number of pulses produced by the larvae of *T. granarium* and *T. variabile* ($P<0.05$). Significant differences between adults and larvae in peak sounds and number of pulses ($P<0.05$). [Conclusion] In the sounds of the two *Trogoderma* feeding on peanut, The peak sounds of adult *T. granarium*[(- 11.33±0.69) dB]>*T. variabile* adult[(- 13.37±1.06) dB]. The number of pulses of *T. granarium* larvae (21.40±3.37)<*T. variabile* larvae (27.40±1.63). The peak sounds and number of pulses (5.60±0.60) of adult *T. granarium*<the peak sounds[(- 6.85±0.51) dB] and number of pulses of larvae. The peak sounds and number of pulses[2.20±0.59] of adult *T. variabile*<the peak sounds[(- 4.96±0.39) dB] and number of pulses of larvae. This indicates that the species and stages of the two *Trogoderma* can be distinguished by peak sounds or number of pulses. In the two *Trogoderma* feeding on corn, the peak sounds[(- 23.44±1.80) dB] and frequency peak[(4 451.50±165.34) Hz] of adult *T. granarium*<the peak asounds[(- 18.02±0.70) dB] and frequency peak [(4 857.50±176.36) Hz] of adult *T. variabile*. The number of pulses of *T. granarium* larvae (16.20±1.16)<*T. variabile* larvae (23.60±2.41). The peak sounds and number of pulses[(1.75±0.19)] of adult *T. granarium*<the peak sounds[(- 7.68±0.65) dB] and number of pulses of larvae. The peak sounds and number of pulses (1.60±0.65) of adult *T. variabile*<the peak sounds [(- 7.24±0.66) dB] and number of pulses of larvae. This indicates that the species and stages of the two *Trogoderma* can be distinguished by peak sounds and number of pulses, and the species of the two adult *Trogoderma* can be distinguished by frequency peak.

Key words *Trogoderma granarium*; *Trogoderma variabile*; bioacoustic; peak of insect sounds; number of pulses; peak of frequency

斑皮蠹属 *Trogoderma* 隶属于鞘翅目 Coleoptera 皮蠹科 Dermestidae, 现已记载 134 个物种, 其中一些害虫是造成储藏谷物数量和质量损失的罪魁祸首 (Hava, 2011; Agarwal *et al.*, 2020)。谷斑皮蠹 *Trogoderma granarium* 是世界上最重要的入侵物种之一 (Athanassiou *et al.*, 2019), 已被欧洲和地中海植物保护组织 (European and Mediterranean Plant Protection Organization, EPPO) 认定为 A2 级检疫性有害生物, 并被列入 100 种有害外来物种名单 (Lowe *et al.*, 2000), 是加拿大、澳大利亚、俄罗斯和美国等许多主要谷物生产国家的检疫物种 (Athanassiou *et al.*, 2019)。其成虫寿命短, 不飞行, 在国家之间的入侵通常由商品和货物携带卵和幼虫实现 (Kavallieratos *et al.*, 2017; Athanassiou *et al.*, 2019)。谷斑皮蠹的寄主十分广泛, 据不完全统计, 其寄主涉及原料、谷物和奶粉等 100 多种不同商品 (Athanassiou *et al.*,

2015; Kavallieratos *et al.*, 2019)。花斑皮蠹 *Trogoderma variabile* 是斑皮蠹属最常见的物种之一, 在世界许多国家包括美国和澳大利亚都有分布 (Campbell and Mullen, 2004; Agarwal *et al.*, 2020; Castañé *et al.*, 2020)。其成虫具有飞行能力, 可在仓储设施内外远距离飞行 (Campbell and Arbogast, 2004; McKay *et al.*, 2017), 不取食整粒谷物, 偏好的寄主包括大麦、小麦、混合动物饲料、加工和碾磨的谷物、杂粮制品和花粉, 被认为是储藏谷物的次要害虫 (Arthur and Kelley, 2014; Wilkins *et al.*, 2020)。

谷斑皮蠹和花斑皮蠹危害是造成储粮采后损失的主要原因之一, 在虫害发生早期进行实时检测, 提早发现虫害发生位置, 有助于及时以虫害中心为重点控制害虫, 实施害虫综合治理, 防止经济损失。目前可以做到早期发现虫害的技术主要有图像识别、声音信号识别、气味识别以及近红外光谱技术等 (Adedeji *et al.*, 2020;

Anukiruthika *et al.*, 2021)。图像识别能识别粮堆表面的害虫,但无法识别粮粒内部害虫,且受光线影响严重(王凡,2014;陈梅香等,2015)。气体识别具有取样方便、检测快捷、监测灵敏等多种独特优势,但存在传感器的适应性和专一性不足、易与周围气体分子结合发生化学变化等问题(陈亭利等,2022)。红外光谱法的在线检测成本低、计数准确,但对体态相近害虫的区分程度不高(鲁玉杰等,2021)。而声学方法不但能解决上述问题,还能对粮粒内害虫数量进行估算(Mankin and Lapointe, 2003; Bhairavi *et al.*, 2020; 鲁玉杰等, 2021),因此本文选择了声学方法对2种皮蠹进行分类研究。

声学方法依赖于生物声信号(Bioacoustic signal, BASs)的接收和检测,生物声信号是害虫取食谷物或在谷物之间移动时产生的(Fleurat-Lessard *et al.*, 2006; Mankin and Moore, 2010)。利用生物声信号进行分类研究,最关键的一步是从原始声音(环境声音或其他害虫)中识别并提取目标声音的独特特征,这些特征可以在时域、频域上实现。例如,在时域上,环境声音(10 s以上)比害虫产生的声音要长得多(在ms级的范围内),且存在持续性(Mankin *et al.*, 2008; Njoroge *et al.*, 2016)。在频域中,环境声音的最高频率(1 kHz以下)低于害虫(Mankin and Hagstrum, 2011),而不同害虫的最高频率完全不同,例如,红棕象甲 *Rhynchophorus ferrugineus* (Mankin, 2011)、米象 *Sitophilus oryzae* 成虫和幼虫(Fleurat-Lessard *et al.*, 2006; Eliopoulos *et al.*, 2015)、谷蠹 *Rhyzopertha dominica* 成虫和幼虫(Fleurat-Lessard *et al.*, 2006)的最高频率分别在1.3-3.8、2-3及以上、1.3-2、1.5-3.2和1.7-2.5 kHz被检测到。此外,传感器类型也是记录生物声信号的重要因素之一。各种传感器已成功地用于收集各种害虫的声音,包括冷凝器麦克风(Hickling *et al.*, 2000; Mankin and Moore, 2010)、加速度计(Santiago *et al.*, 2017)和压电换能器(Eliopoulos *et al.*, 2015; Sutin *et al.*, 2017)。近年来,储粮害虫的生物声学研究发展迅速(Banga *et al.*, 2019; Sutin *et al.*,

2019; Adedeji *et al.*, 2020),如用声学方法成功鉴定了米象的成虫和幼虫(Mankin *et al.*, 2011)。除储粮害虫外,该方法还成功地鉴定了木材(Siriwardena *et al.*, 2010; Sutin *et al.*, 2019)、土壤(Mankin *et al.*, 2002; Görres and Chesmore, 2019)、水果和蔬菜(Adedeji *et al.*, 2020; Banlawe and Dela Cruz, 2020)等中的昆虫。但关于谷斑皮蠹和花斑皮蠹的生物声学研究较少(Eliopoulos *et al.*, 2015)。因此,本研究选择多用于储粮害虫检测的压电传感器(Mankin and Hagstrum, 2011),通过声音信号识别方法对在不同寄主中的2种皮蠹成、幼虫进行声音特征采集并分析声音参数差异,明确声音是否可以作为2种皮蠹种类和虫态的鉴别方法,为利用声音检测和识别害虫提供参考依据。

1 材料与方法

1.1 材料与设备

实验所用试虫均由苏州海关国家仓储有害生物检疫重点实验室提供,将谷斑皮蠹和花斑皮蠹置于温度为(30±1)℃、相对湿度70%±5%的恒温培养箱(上海博讯医疗生物仪器股份有限公司)内培养,光周期12L:12D。用养虫罐经过一个月的隔离饲养,获得大量成虫和3龄幼虫进行实验。实验所用花生和玉米被手动清洗,洗涤,并在阳光下干燥,以防止任何先前的侵害或化学残留物。所有试验均在苏州海关国家仓储害虫检疫重点实验室进行。

选用压电传感器(天津华江仪表科技有限公司;型号:HJZ9300),研制了容量约为10 kg的声音屏蔽箱,箱型为矩形。音屏蔽箱外壁采用铝合金制成,厚度为20 mm,箱体的尺寸为60 cm×30 cm×37 cm,箱内放置一层40 mm聚氨酯泡沫(图1),40 mm泡沫板的降噪系数(NRC)值为0.80,该泡沫能够降低空气中的噪声,吸收外界振动和噪声避免被麦克风捕获(Njoroge *et al.*, 2016)。

1.2 录制方法

将谷物平铺一层至平板,选取10头昆虫的

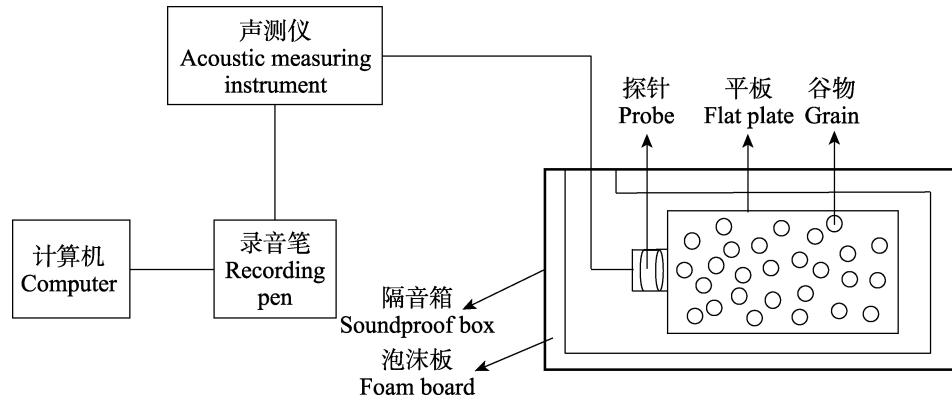


图 1 声学昆虫检测系统示意图

Fig. 1 Schematic diagram of acoustic insect detection system

成虫放到谷物的中心，让其自由活动 30 min 后进行录制，避免由于谷物干扰而降低昆虫活动。每次记录持续 3 min，生物学重复 5 次，技术重复 5 次，每次生物重复时更换实验样本，采样点设置为 44 100 Hz。每次释放虫子前进行一次空白录音以便后期消除杂音。幼虫以同样方法录制。

1.3 时频域分析

快速傅里叶变换是离散傅里叶变换 (Discrete Fourier transform, DFT) 的快速算法。推导过程是先将傅里叶变换公式 $F(w) = \int_{-\infty}^{+\infty} f(t)e^{-j\omega t} dt$ 反变换为 $f(t) = F^{-1}[F(w)] = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(w)e^{j\omega t} dw$ ，其中 w 代表频率， t 代表时间， $e^{-j\omega t}$ 为复变函数。接下来对连续信号 $x(t)$ 进行时域采样，得到一组离散样本 $x(n)$ ，进行傅里叶变换得到离散时间傅里叶变换公式 $X(w) = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi kn}{N}}$ 。继续对频域信号进行采样，即

$$\text{得到 DFT 公式 } X(k) = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi kn}{N}}.$$

1.4 虫声提取

无虫屏蔽箱中未处理的波形图如图 2 (A) 所示，使用声音处理软件 Cool Edit PRO 对录制声音进行滤波处理 (图 2: B)，并确定高通截至频率 4 000 Hz、音量阈值线 -24 dB。图 2 (B) 中横坐标为时间 (s)，纵坐标为振幅 (dB)，表现了声音音量的变化规律。所有录音文件均采用 “.wav” 格式。花生和玉米在不加昆虫的情况下，滤波后的声音波形图基本一致 (图 2: B)。

在声音录制过程中，时间是一个不变量。采用上述数值对取食花生和玉米的谷斑皮蠹、花斑皮蠹的声谱进行滤波处理，如图 3 (A-D)。

1.5 声音参数提取

昆虫的每个生物声信号都是脉冲的集合，分析脉冲信号的过程就是时域分析。统计滤波后谷斑皮蠹和花斑皮蠹的成虫和幼虫在花生和玉米上产生的所有脉冲数，并使用软件 Cool Edit

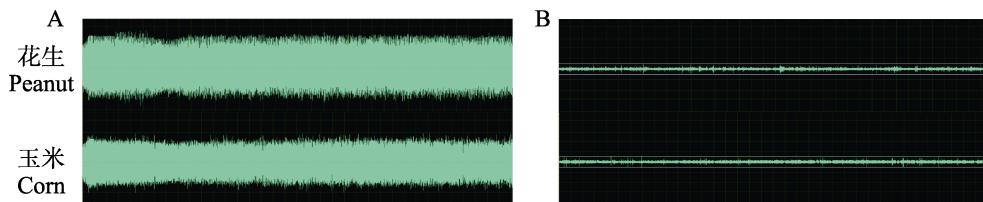


图 2 花生和玉米中无害虫取食声音滤波前后波形图

Fig. 2 Peanut and corn without pests feeding sound waveform before and after filtering

A. 滤波前；B. 滤波后。A. Before filtering; B. After filtering.

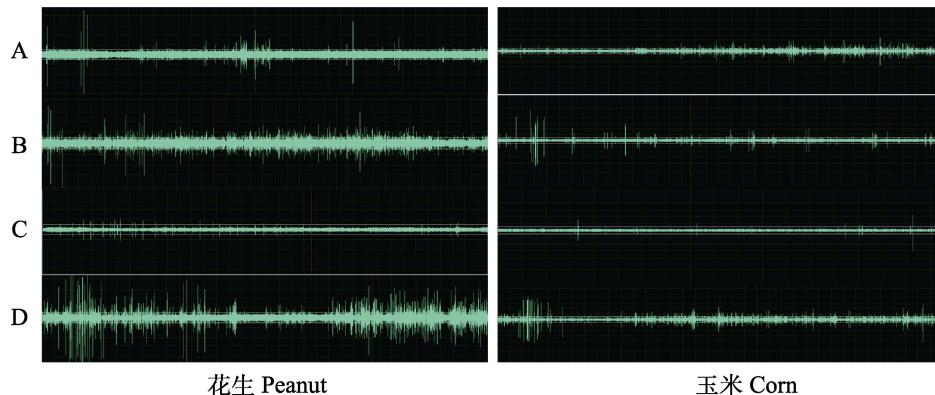


图 3 花生和玉米中谷斑皮蠹和花斑皮蠹取食声音滤波后波形图

Fig. 3 Waveforms of *Trogoderma granarium* and *Trogoderma variabile* feeding sound in peanut and corn after filtering

A. 谷斑皮蠹成虫; B. 谷斑皮蠹幼虫; C. 花斑皮蠹成虫; D. 花斑皮蠹幼虫。

A. Adults of *T. granarium*; B. Larvae of *T. granarium*; C. Adults of *T. variabile*; D. Larvae of *T. variabile*.

PRO 对滤波后的声音进行波形统计分析, 读取虫声峰值。

频率是事件发生在特定时间内的大小, 分析频率相关参数的过程就是频域分析。通过软件 Cool Edit PRO 对录音进行 FFT 变换后, 以时间

(s)为 x 轴, 频率(Hz)为 y 轴绘制声谱图(图 4: A-D), 用于分析声音频率的变化规律。通过软件 Cool Edit PRO 上的频谱分析器以频率为 x 轴 (Hz), 音量 (dB)为 y 轴绘制功率谱图, 分析并统计出最高频率即频率峰值。

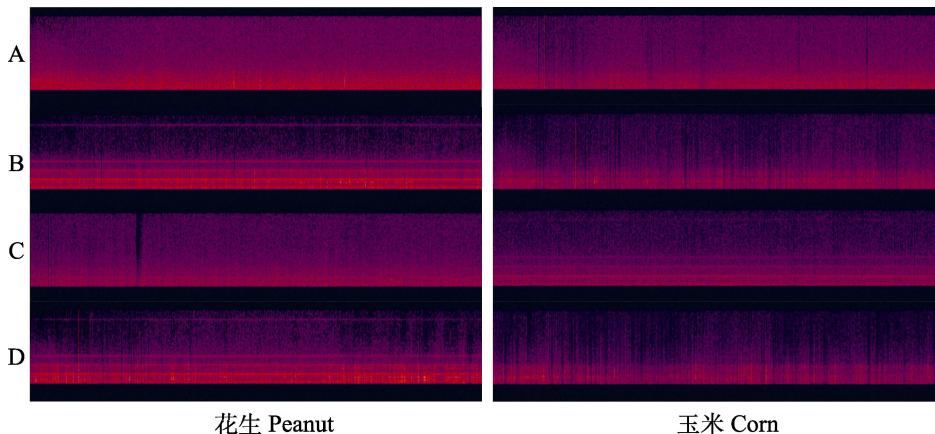


图 4 花生和玉米中谷斑皮蠹和花斑皮蠹取食声音滤波后频谱图

Fig. 4 Spectrum of *Trogoderma granarium* and *Trogoderma variabile* feeding sound in peanut and corn after filtering

A. 谷斑皮蠹成虫; B. 谷斑皮蠹幼虫; C. 花斑皮蠹成虫; D. 花斑皮蠹幼虫。

A. Adults of *T. granarium*; B. Larvae of *T. granarium*; C. Adults of *T. variabile*; D. Larvae of *T. variabile*.

1.6 数据分析

实验原始数据用 Microsoft Excel 2021 记录。使用 Kolmogorov-Smirnov 检验对数据集 2 种皮蠹成虫和幼虫在花生中的声音参数、2 种皮蠹成虫和幼虫在玉米中的声音参数进行正态性检验。

如果数据集呈正态分布, 则通过单因素方差分析 (One-way ANOVA) 来检验统计学意义, 如果数据集不呈现正态分布, 则使用 Kruskal-Wallis 检验和 Stepwise step-down 检验对非正态数据进行统计分析, 评价数据间差异的统计学意义。采

用独立样本 t 检验 (Student's t -test) 方法对花生和玉米中的虫声峰值、脉冲数和频率峰值进行差异显著性分析 ($P<0.05$)。

2 结果与分析

2.1 谷斑皮蠹和花斑皮蠹取食花生的声音参数比较

对谷斑皮蠹和花斑皮蠹成、幼虫取食花生的声音参数进行统计学分析 (表 1)。从种类分析, 谷斑皮蠹和花斑皮蠹成虫在虫声峰值上存在显著差异 ($P<0.05$), 谷斑皮蠹成虫的虫声峰值 [(-11.33±0.69) dB] 大于花斑皮蠹成虫 [(-13.37±1.06) dB]。说明可以通过虫声峰值区分谷斑皮蠹和花斑皮蠹成虫。谷斑皮蠹和花斑皮蠹幼虫在脉冲数上存在显著差异 ($P<0.05$), 谷斑皮蠹幼虫的脉冲数 [(21.40±3.37) 个] 低于

花斑皮蠹幼虫 [(27.40±1.63) 个]。说明可以通过脉冲数区分谷斑皮蠹和花斑皮蠹幼虫。从虫态分析, 谷斑皮蠹成虫和幼虫在虫声峰值和脉冲数上均存在显著差异 ($P<0.05$), 谷斑皮蠹成虫的虫声峰值小于幼虫的虫声峰值 [(-6.85±0.51) dB], 且脉冲数 [(5.60±0.60) 个] 低于幼虫的脉冲数。说明可以通过虫声峰值和脉冲数区分谷斑皮蠹成虫和幼虫。花斑皮蠹成虫和幼虫在虫声峰值和脉冲数上存在显著差异 ($P<0.05$), 其成虫的虫声峰值和脉冲数小于幼虫 [虫声峰值: (-4.96±0.39) dB, 脉冲数: (2.20±0.59) 个]。说明可以通过虫声峰值和脉冲数区分花斑皮蠹成虫和幼虫。在谷斑皮蠹和花斑皮蠹取食花生的声音参数中, 通过虫声峰值可以区分 2 种斑皮蠹的成虫种类, 通过脉冲数可以区分 2 种斑皮蠹的幼虫种类, 通过虫声峰值或脉冲数可以区分 2 种斑皮蠹的虫态。

表 1 谷斑皮蠹和花斑皮蠹取食花生的声音参数

Table 1 Sound parameters of *Trogoderma granarium* and *Trogoderma variabile* feeding on peanut

实验样本 Experimental specimen	虫声峰值 (dB) Peak of insect sounds (dB)	脉冲数 (个) Number of pulses	频率峰值 (Hz) Peak of frequency (Hz)
谷斑皮蠹成虫 Adults of <i>T. granarium</i>	-11.33±0.69 c	5.60±0.60 b	5 433.24±105.55 a
谷斑皮蠹幼虫 Larvae of <i>T. granarium</i>	-6.85±0.51 a	21.40±3.37 c	5 511.60±104.88 a
花斑皮蠹成虫 Adults of <i>T. variabile</i>	-13.37±1.06 b	2.20±0.59 b	5 097.10±272.99 a
花斑皮蠹幼虫 Larvae of <i>T. variabile</i>	-4.96±0.39 a	27.40±1.63 a	5 536.65±176.52 a
空白对照 CK	-34.81±0.55 d	—	—

表中数据为平均值±标准误, 同行数据后不同字母表示差异显著 ($P<0.05$, 单因素方差分析)。下表同。

Data in the table are mean±SE, and followed by different letters in the same row indicate significant difference ($P<0.05$, One-way ANOVA). The same below.

2.2 谷斑皮蠹和花斑皮蠹取食玉米的声音参数比较

对谷斑皮蠹和花斑皮蠹成、幼虫取食玉米的声音参数进行统计学分析。由表 2 可知, 从种类分析, 谷斑皮蠹和花斑皮蠹成虫在虫声峰值和频率峰值上均存在显著差异 ($P<0.05$), 谷斑皮蠹成虫的虫声峰值 [(-23.44±1.80) dB] 小于花斑皮蠹成虫 [(-18.02±0.70) dB], 谷斑皮蠹成虫的频率峰值 [(4 451.50±165.34) Hz] 低于花斑皮

蠹成虫 [(4 857.50±176.36) Hz]。说明可以通过虫声峰值和频率峰值区分谷斑皮蠹和花斑皮蠹成虫。谷斑皮蠹和花斑皮蠹幼虫的脉冲数存在显著差异 ($P<0.05$), 谷斑皮蠹幼虫的脉冲数 [(16.20±1.16) 个] 小于花斑皮蠹幼虫的脉冲数 [(23.60±2.41) 个]。说明可以通过脉冲数区分谷斑皮蠹和花斑皮蠹幼虫。从虫态分析, 谷斑皮蠹成虫和幼虫的虫声峰值、脉冲数和频率峰值上均存在显著差异 ($P<0.05$), 其成虫的虫声峰值、脉冲数和频率峰值均小于幼虫 [虫声峰

值: (-7.68 ± 0.65) dB], 脉冲数: (1.75 ± 0.19)个, 频率峰值: (5024.79 ± 63.29) Hz]。说明通过虫声峰值、脉冲数和频率峰值均可区分谷斑皮蠹成虫和幼虫。花斑皮蠹成虫和幼虫的虫声峰值和脉冲数上均存在显著差异 ($P < 0.05$), 花斑皮蠹成虫的虫声峰值小于幼虫[(-7.24 ± 0.66) dB], 且脉冲数[(1.60 ± 0.65) 个]低于幼虫的脉冲数。

说明可以通过虫声峰值和脉冲数区分花斑皮蠹成虫和幼虫。在谷斑皮蠹和花斑皮蠹取食玉米的声音参数中, 通过虫声峰值或频率峰值可以区分2种皮蠹成虫的种类, 通过脉冲数可以区分2种皮蠹幼虫的种类, 通过虫声峰值、脉冲数或频率峰值可以区分谷斑皮蠹的虫态, 通过虫声峰值或脉冲数可以区分花斑皮蠹的虫态。

表 2 谷斑皮蠹和花斑皮蠹取食玉米的声音参数

Table 2 Sound parameters of *Trogoderma granarium* and *Trogoderma variabile* feeding on corn

实验样本 Experimental specimen	虫声峰值 (dB) Peak of insect sounds (dB)	脉冲数 (个) Number of pulses	频率峰值 (Hz) Peak of frequency (Hz)
谷斑皮蠹成虫 Adults of <i>T. granarium</i>	-23.44 ± 1.80 c	1.75 ± 0.19 b	4451.50 ± 165.34 c
谷斑皮蠹幼虫 Larvae of <i>T. granarium</i>	-7.68 ± 0.65 a	16.20 ± 1.16 c	5024.79 ± 63.29 a
花斑皮蠹成虫 Adults of <i>T. variabile</i>	-18.02 ± 0.70 b	1.60 ± 0.65 b	4857.50 ± 176.36 a
花斑皮蠹幼虫 Larvae of <i>T. variabile</i>	-7.24 ± 0.66 a	23.60 ± 2.41 a	5098.26 ± 100.52 a
空白对照 CK	-38.03 ± 1.23 d	—	—

2.3 花生和玉米中谷斑皮蠹和花斑皮蠹的虫声参数差异

比较谷斑皮蠹和花斑皮蠹成、幼虫在花生和玉米中的声音参数并进行统计学分析。从图5可以看出, 谷斑皮蠹成虫取食花生和玉米声音的虫声峰值存在显著差异 ($P < 0.05$), 而幼虫取食花

生和玉米声音的虫声峰值无统计学差异 ($P > 0.05$)。花斑皮蠹成虫和幼虫取食花生和玉米声音的虫声峰值存在显著差异 ($P < 0.05$)。总体表现为2种皮蠹成虫和幼虫取食花生的虫声峰值高于2种皮蠹成虫和幼虫取食玉米的虫声峰值, 说明了2种皮蠹成虫和幼虫取食花生所产生的声音音量更大。

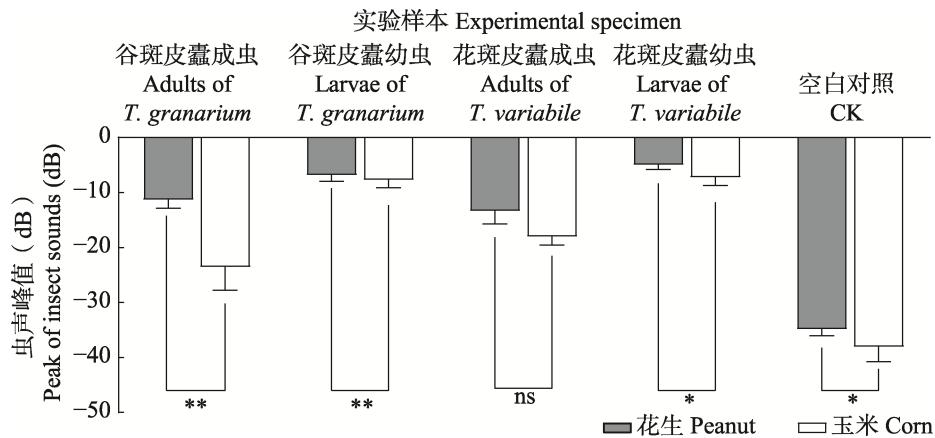


图 5 谷斑皮蠹和花斑皮蠹取食花生和玉米的虫声峰值差异

Fig. 5 Difference of insect sound peak value of *Trogoderma granarium* and *Trogoderma variabile* feeding on peanut and corn

图中数据以平均值±标准误表示, ns 表示差异不显著, 星号表示统计学差异显著 ($* P < 0.05$, $** P < 0.01$, 独立样本 t -检验)。下图同。

Data in the figure are means±SE, ns indicates no significant difference, and asterisks indicate statistically significant difference ($* P < 0.05$, $** P < 0.01$, Student's t -test). The same below.

从图 6 可以看出, 谷斑皮蠹成虫取食花生和玉米的脉冲数存在显著差异 ($P<0.05$) , 幼虫取食花生和玉米的脉冲数无统计学差异 ($P>0.05$) 。花斑皮蠹成虫取食花生和玉米的脉冲数无统计学差异 ($P>0.05$) , 幼虫取食花生和玉米的脉冲数存在显著差异 ($P<0.05$) 。总体表现为 2 种皮蠹成虫和幼虫取食花生的脉冲数多于 2 种皮蠹成虫和幼虫取食玉米的脉冲数, 说明了 2 种皮蠹成虫和幼虫取食花生所产生的声音次数更多。

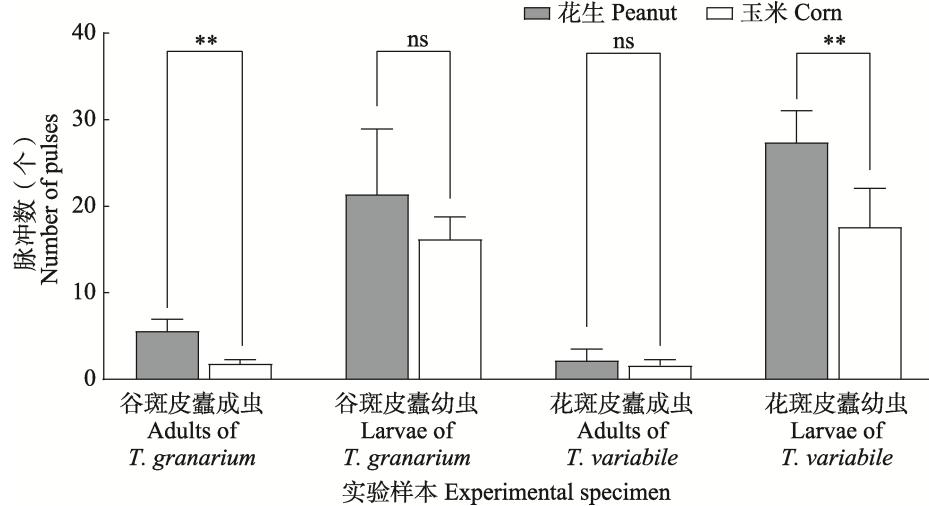


图 6 谷斑皮蠹和花斑皮蠹取食花生和玉米的脉冲数差异

Fig. 6 Difference of pulse number of *Trogoderma granarium* and *Trogoderma variabile* feeding on peanut and corn

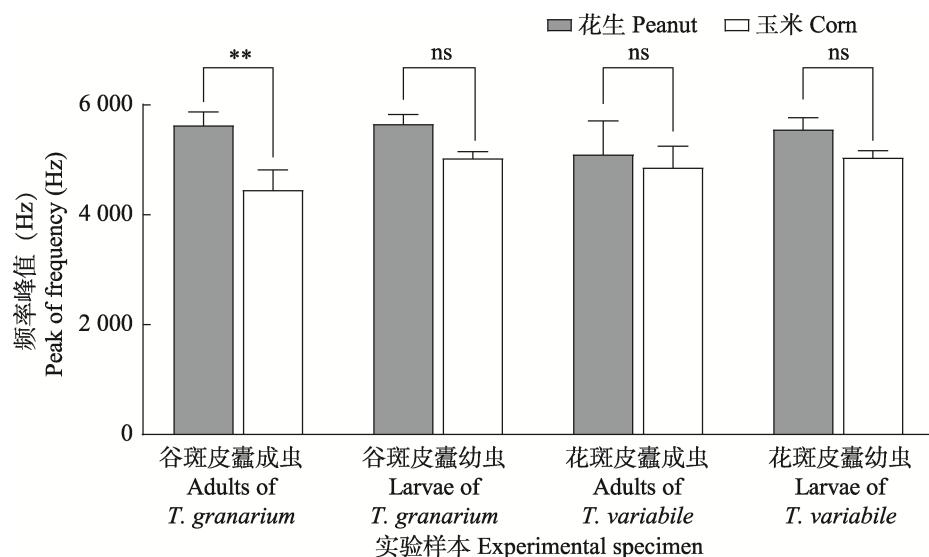


图 7 谷斑皮蠹和花斑皮蠹取食花生和玉米的频率峰值差异

Fig. 7 Difference of frequency peak value of *Trogoderma granarium* and *Trogoderma variabile* feeding on peanut and corn

从图 7 可以看出, 谷斑皮蠹成虫取食花生和玉米的频率峰值存在显著差异 ($P<0.05$) , 幼虫取食花生和玉米的频率峰值无统计学差异 ($P>0.05$) 。花斑皮蠹成虫和幼虫取食花生和玉米的频率峰值无统计学差异 ($P>0.05$) 。总体表现为 2 种皮蠹成虫和幼虫取食花生的频率峰值高于 2 种皮蠹成虫和幼虫取食玉米的频率峰值, 说明了 2 种皮蠹成虫和幼虫取食花生所产生的声音音调更高。

比较谷斑皮蠹和花斑皮蠹成、幼虫取食花生和玉米的声音参数发现,并非所有数据都存在显著差异,但无论是否存在显著差异,以花生为寄主的昆虫声音参数总是高于以玉米为寄主的昆虫声音参数,说花生更适合作为寄主进行谷斑皮蠹和花斑皮蠹的声学研究。

3 结论与讨论

声学方法是基于接收和识别昆虫摄食和运动声音的一种监测方法。声音参数的分析可以提供有关害虫行为特征的有用信息,以确定其种类和虫态(Neethirajan *et al.*, 2007)。皮蠹是具有侵袭性的储粮害虫,但对其生物声特征的研究却很少。因此,本文使用自制隔音设备和声测仪录制了谷斑皮蠹和花斑皮蠹成、幼虫在花生和玉米中的生物声音,对它们的生物声学特征进行了研究。发现在谷斑皮蠹和花斑皮蠹取食花生的声音参数中,通过虫声峰值可以区分2种皮蠹成虫的种类,通过脉冲数可以区分2种皮蠹幼虫的种类,通过虫声峰值或脉冲数可以区分2种皮蠹的虫态。在谷斑皮蠹和花斑皮蠹取食玉米的声音参数中,通过虫声峰值或频率峰值可以区分2种皮蠹成虫的种类,通过脉冲数可以区分2种皮蠹幼虫的种类,通过虫声峰值、脉冲数或频率峰值可以区分谷斑皮蠹的虫态,通过虫声峰值或脉冲数可以区分花斑皮蠹的虫态。因此,虫声峰值和脉冲数可以作为区分2种皮蠹种类和虫态的特征参数。此外,与玉米相比,花生更适合作为谷斑皮蠹和花斑皮蠹的寄主进行声学研究。

早期关于昆虫生物声分析的研究发现,在绿豆和鹰嘴豆中,四纹豆象成虫 *Callosobruchus maculatus* 和绿豆象成虫 *C. chinensis* 可以通过声音参数进行分类鉴定(Banga *et al.*, 2019)。比较谷斑皮蠹和花斑皮蠹在同种粮食上的参数差异可以发现,谷斑皮蠹幼虫在花生和玉米中的虫声峰值、脉冲数以及频率峰值都低于花斑皮蠹幼虫,这可能与它们的体型差异有关。谷斑皮蠹3龄幼虫平均体长4.0-6.7 mm,成虫平均体长1.8-3.0 mm(王新国, 2009)。花斑皮蠹3龄幼虫平均体长6-9 mm,成虫平均体长2.4-4.5 mm(赵

姝荣等, 2008)。在谷物中,大尺寸的昆虫如米象和赤拟谷盗 *Tribolium castaneum* 比小尺寸的昆虫如锈赤扁谷盗 *Cryptolestes ferrugineus* 和谷蠹更容易检测到(Hagstrum and Flinn, 1993; Mankin *et al.*, 2011)。这也是以3龄幼虫开展实验的原因,相比于1-2龄幼虫,3龄幼虫的体型更大,相比于末龄幼虫,3龄幼虫取食频率相对频繁,但在成虫中却未遵循体积大更易检测到这一规律。在本研究中发现,在花生中谷斑皮蠹成虫的虫声峰值、脉冲数、频率峰值都高于花斑皮蠹成虫。在玉米中谷斑皮蠹成虫的虫声峰值、脉冲数、频率峰值都低于花斑皮蠹成虫。这可能与花斑皮蠹成虫具有假死性这一生物学习性相关(王云果, 2007)。同时说明了在使用生物声学进行昆虫的分类鉴定时,选择幼虫相比于选择成虫干扰更少、更合适。

单独就谷斑皮蠹和花斑皮蠹进行分析,可以发现在花生或玉米中幼虫的虫声峰值、脉冲数、频率峰值都高于成虫。恰好支持了皮蠹主要在幼虫期危害粮食,卵孵化为幼虫后,需要长时间摄取食物,积累热量,成虫不取食,产卵后即死亡这一行为习性(王云果等, 2009; Athanassiou *et al.*, 2016)。这与Njoroge等(2017)在菜豆象 *Acanthoscelides obtectus* 中发现其成虫的脉冲数低于幼虫结果一致。此外,也有研究表明,通过昆虫声音参数的研究,还可以进行昆虫性别的判断。如Azizi Farsani等(2024)发现谷斑皮蠹雌成虫脉冲数和虫声峰值均高于雄成虫。

单独比较谷斑皮蠹和花斑皮蠹取食花生和玉米声音的参数差异,发现成、幼虫取食花生的声音参数均大于取食玉米的声音参数,说明取食花生发出的声音音量更大、次数更多、音调更高,更适合进行2种皮蠹种类和虫态的鉴定。研究2种寄主的营养成分可知,花生中棕榈酸和硬脂酸的含量远高于玉米,这2种饱和脂肪酸都是谷斑皮蠹和花斑皮蠹的偏好物质(Levinson *et al.*, 1978; Wilkins *et al.*, 2020),可能是造成这一结果的原因。Banga等(2019)在绿豆象和四纹豆象的生物声研究中发现,由于豆象的偏好性选择,导致绿豆象成虫在绿豆中的虫声峰值高于在

鹰嘴豆中,四纹豆象成虫在绿豆中的虫声峰值低于在鹰嘴豆中。说明在利用生物声进行昆虫种类和虫态的鉴定时,应尽量选择昆虫的偏好性寄主。

本研究证实了声学方法在不同昆虫种类(谷斑皮蠹和花斑皮蠹)、不同生长阶段(幼虫和成虫)鉴定中的巨大潜力,且表明利用声学方法进行昆虫种类和虫态的鉴定时,应选择昆虫的偏好性寄主。近年来,深度学习技术在物种识别上的应用已越来越多,本研究下一步将丰富虫声数据集的种类范围,建立虫声声波数据库,开发声音识别算法,建立适用于隐蔽在粮食中害虫虫声声波的智能诊疗技术,实现粮食中害虫成、幼虫种类和虫态的智能检测与鉴定。

参考文献 (References)

- Adedeji AA, Ekramirad N, Rady A, Hamidisepehr A, Donohue KD, Villanueva RT, Parrish CA, Li MX, 2020. Non-destructive technologies for detecting insect infestation in fruits and vegetables under postharvest conditions: A critical review. *Foods*, 9(7): 927.
- Agarwal M, Al-Shuwaili T, Nugaliyadde A, Wang PH, Wong KW, Ren YL, 2020. Identification and diagnosis of whole body and fragments of *Trogoderma granarium* and *Trogoderma variabile* using visible near infrared hyperspectral imaging technique coupled with deep learning. *Computers and Electronics in Agriculture*, 173: 105438.
- Anukiruthika T, Jian FJ, Jayas DS, 2021. Movement and behavioral response of stored product insects under stored grain environments-a review. *Journal of Stored Products Research*, 90: 101752.
- Arthur F, Kelley P, 2014. *Trogoderma variabile*: A model species for control of dermestids in museums. 11th International Working Conference on Stored Product Protection. Thailand: 24–28.
- Athanassiou CG, Kavallieratos NG, Boukouvala MC, 2016. Population growth of the khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae) on different commodities. *Journal of Stored Products Research*, 69: 72–77.
- Athanassiou CG, Kavallieratos NG, Boukouvala MC, Mavroforos ME, Kontodimas DC, 2015. Efficacy of alpha-cypermethrin and thiamethoxam against *Trogoderma granarium* Everts (Coleoptera: Dermestidae) and *Tenebrio molitor* L. (Coleoptera: Tenebrionidae) on concrete. *Journal of Stored Products Research*, 62: 101–107.
- Athanassiou CG, Phillips TW, Wakil W, 2019. Biology and control of the khapra beetle, *Trogoderma granarium*, a major quarantine threat to global food security. *Annual Review of Entomology*, 64: 131–148.
- Azizi Farsani P, Sakenian Dehkordi N, Ebrahimi R, Nemati A, Taghizadeh Dehkordi M, 2024. Bioacoustics of *Trogoderma granarium* Everts (Coleoptera: Dermestidae). *Journal of Asia-Pacific Entomology*, 27(1): 102189.
- Banga KS, Kotwaliwale N, Mohapatra D, Giri SK, Babu VB, 2019. Bioacoustic detection of *Callosobruchus chinensis* and *Callosobruchus maculatus* in bulk stored chickpea (*Cicer arietinum*) and green gram (*Vigna radiata*). *Food Control*, 104: 278–287.
- Banlawe IAP, Dela Cruz JC, 2020. Acoustic sensors for mango pulp weevil (*Stretochenus frigidus*) detection. 2020 IEEE 10th International Conference on System Engineering and Technology (ICSET). Malaysia: 191–195.
- Bhairavi KS, Bhattacharyya B, Manpoong NS, Das PPG, Devi EB, Bhagawati S, 2020. Recent advances in exploration of acoustic pest management: A review. *Journal of Entomology and Zoology Studies*, 8: 2056–2061.
- Campbell JF, Arbogast RT, 2004. Stored-product insects in a flour mill: Population dynamics and response to fumigation treatments. *Entomology Experimentalis et Applicata*, 112(3): 217–225.
- Campbell JF, Mullen MA, 2004. Distribution and dispersal behavior of *Trogoderma variabile* and *Plodia interpunctella* outside a food processing plant. *Journal of Economic Entomology*, 97(4): 1455–1464.
- Castañé C, Agustí N, del Estal P, Riudavets J, 2020. Survey of *Trogoderma* spp. in Spanish mills and warehouses. *Journal of Stored Products Research*, 88: 101661.
- Chen MX, Yang XT, Shi BC, Li WY, Du XW, Li M, Sun CH, 2015. Research progress and prospect of technologies for automatic identifying and counting of pests. *Journal of Environmental Entomology*, 37(1): 176–183. [陈梅香, 杨信廷, 石宝才, 李文勇, 杜晓伟, 李明, 孙传恒, 2015. 害虫自动识别与计数技术研究进展与展望. 环境昆虫学报, 37(1): 176–183.]
- Chen TL, Wang TN, Yang YT, Ye SP, Miao QH, 2022. Research review of odor recognition technology. *Science and Technology & Innovation*, 2022(9): 43–45, 51. [陈亭利, 王天娜, 杨雨婷, 叶世鹏, 苗卿华, 2022. 气味识别技术研究综述. 科技与创新, 2022(9): 43–45, 51.]
- Eliopoulos PA, Potamitis I, Kontodimas DC, Givropoulou EG, 2015.

- Detection of adult beetles inside the stored wheat mass based on their acoustic emissions. *Journal of Economic Entomology*, 108(6): 2808–2814.
- Fleurat-Lessard F, Tomasini B, Kostine L, Fuzeau B, 2006. Acoustic detection and automatic identification of insect stages activity in grain bulks by noise spectra processing through classification algorithms. 9th International Working Conference on Stored Product Protection. Brazil: 476–486.
- Görres CM, Chesmore D, 2019. Active sound production of scarab beetle larvae opens up new possibilities for species-specific pest monitoring in soils. *Scientific Reports*, 9(1): 10115.
- Hagstrum DW, Flinn PW, 1993. Comparison of acoustical detection of several species of stored-grain beetles (Coleoptera: Curculionidae, Tenebrionidae, Bostrichidae, Cucujidae) over a range of temperatures. *Journal of Economic Entomology*, 86(4): 1271–1278.
- Hava J, 2011. A new *Trogoderma* species from Uruguay (Coleoptera: Dermestidae: Megatominae). *Studies and Reports of District Museum Prague-East Taxonomical Series*, 7: 117–120.
- Hickling R, Lee P, Velea D, Dennehy TJ, Patin AI, 2000. Acoustic system for rapidly detecting and monitoring pink bollworm in cotton bolls. Beltwide Cotton Conference 2000 San Antonio TX. United States: Texas, Tennessee.
- Kavallieratos NG, Athanassiou CG, Guedes RNC, Drempela JD, Boukouvala MC, 2017. Invader competition with local competitors: Displacement or coexistence among the invasive khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae), and two other major stored-grain beetles? *Frontiers in Plant Science*, 8: 1837.
- Kavallieratos NG, Karagianni ES, Papanikolaou NE, 2019. Life history of *Trogoderma granarium* Everts (Coleoptera: Dermestidae) on peeled barley, peeled oats and triticale. *Journal of Stored Products Research*, 84: 101515.
- Levinson AR, Levinson HZ, Schwaiger H, Cassidy RF, Silverstein RM, 1978. Olfactory behavior and receptor potentials of the khapra beetle *Trogoderma granarium* (Coleoptera: Dermestidae) induced by the major components of its sex pheromone, certain analogues, and fatty acid esters. *Journal of Chemical Ecology*, 4: 95–108.
- Lowe S, Browne M, Boudjelas S, Poorter MD, 2000. 100 of the world's worst invasive alien species: A selection from the global invasive species database. Auckland. 12.
- Lu YJ, Wang WJ, Ren TY, Lu SH, Wang ZY, 2021. Research progress of intelligent monitoring and early warning system for stored grain pests. *Science and Technology of Cereals Oils and Foods*, 29(3): 208–214. [鲁玉杰, 王文敬, 任天一, 卢少华, 王争艳, 2021. 储藏物害虫智能化监测与预警系统研究进展. 粮油食品科技, 29(3): 208–214.]
- Mankin RW, 2011. Recent developments in the use of acoustic sensors and signal processing tools to target early infestations of red palm weevil in agricultural environments. *Florida Entomologist*, 94(4): 761–765.
- Mankin RW, Hagstrum DW, Smith MT, Roda AL, Kairo MTK, 2011. Perspective and promise: A century of insect acoustic detection and monitoring. *American Entomologist*, 57(1): 30–44.
- Mankin RW, Hagstrum DW, 2011. Acoustic monitoring of insects// Hagstrum DW, Phillips TW, Cuperus G (eds.). *Stored Product Protection*. Manhattan, Kansas: Kansas State University Press. 1–7.
- Mankin RW, Lapointe SL, 2003. Listening to the larvae: Acoustic detection of *Diaprepes abbreviatus* (L.). *Selected Proceedings of the Florida State Horticultural Society*, 116: 304–308.
- Mankin RW, Mizrahi A, Hetzroni A, Levsky S, Nakache Y, Soroker V, 2008. Temporal and spectral features of sounds of wood-boring beetle larvae: Identifiable patterns of activity enable improved discrimination from background noise. *Florida Entomologist*, 91(2): 241–248.
- Mankin RW, Moore A, 2010. Acoustic detection of *Oryctes rhinoceros* (Coleoptera: Scarabaeidae: Dynastinae) and *Nasutitermes luzonicus* (Isoptera: Termitidae) in palm trees in urban Guam. *Journal of Economic Entomology*, 103(4): 1135–1143.
- Mankin RW, Osbrink WL, Oi FM, Anderson JB, 2002. Acoustic detection of termite infestations in urban trees. *Journal of Economic Entomology*, 95(5): 981–988.
- McKay T, White AL, Starkus LA, Arthur FH, Campbell JF, 2017. Seasonal patterns of stored-product insects at a rice mill. *Journal of Economic Entomology*, 110(3): 1366–1376.
- Neethirajan S, Karunakaran C, Jayas DS, White NDG, 2007. Detection techniques for stored-product insects in grain. *Food Control*, 18(2): 157–162.
- Njoroge AW, Affognon H, Mutungi C, Richter U, Hensel O, Rohde B, Mankin RW, 2017. Bioacoustics of *Acanthoscelides obtectus* (Coleoptera: Chrysomelidae: Bruchinae) on *Phaseolus vulgaris* (Fabaceae). *Florida Entomologist*, 100(1): 109–115.
- Njoroge AW, Affognon H, Mutungi C, Rohde B, Richter U, Hensel O, Mankin RW, 2016. Frequency and time pattern differences in acoustic signals produced by *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and *Sitophilus zeamais* (Motschulsky)

- (Coleoptera: Curculionidae) in stored maize. *Journal of Stored Products Research*, 69: 31–40.
- Santiago RMC, Rabano SL, Billones RKD, Calilung EJ, Dadios EP, 2017. Insect detection and monitoring in stored grains using MFCCs and artificial neural network. TENCON 2017-2017 IEEE Region 10 Conference. 2542–2547.
- Siriwardena KAP, Fernando LCP, Nanayakkara N, Perera KFG, Kumara ADNT, Nanayakkara T, 2010. Portable acoustic device for detection of coconut palms infested by *Rynchophorus ferrugineus* (Coleoptera: Curculionidae). *Crop Protection*, 29(1): 25–29.
- Sutin A, Flynn T, Salloum H, Sedunov N, Hull SH, 2017. Vibro-acoustic methods of insect detection in agricultural shipments and wood packing materials. 2017 IEEE International Symposium on Technologies for Homeland Security (HST). 1–6.
- Sutin A, Yakubovskiy A, Salloum HR, Flynn TJ, Sedunov N, Nadel H, 2019. Towards an automated acoustic detection algorithm for wood-boring beetle larvae (Coleoptera: Cerambycidae and Buprestidae). *Journal of Economic Entomology*, 112(3): 1327–1336.
- Wang F, 2014. Study of feature extraction and recognition of stored product pests. Master dissertation. Qingdao: Qingdao University of Science and Technology. [王凡, 2014. 藏储物害虫特征提取与识别分类研究. 硕士学位论文. 青岛: 青岛科技大学.]
- Wang XG, 2009. Comparison of larval morphology between *Trogoderma granarium* Everts and *Trogoderma glabrum* Herbst. *Plant Quarantine*, 23(1): 18–20, 63. [王新国, 2009. 谷斑皮蠹和黑斑皮蠹幼虫形态比较. 植物检疫, 23(1): 18–20, 63.]
- Wang YG, 2007. Study on Biological character and control technique *Trogoderma variabile*. Master dissertation. Shaanxi: Northwest A&F University. [王云果, 2007. 花斑皮蠹的生物学特性及防治技术研究. 硕士学位论文. 陕西: 西北农林科技大学.]
- Wang YG, Gao ZH, Bu SH, Zhao SR, 2009. Behavior of adult *Trogoderma variabile*. *Journal of Northwest Forestry University*, 24(2): 91–93. [王云果, 高智辉, 卜书海, 赵姝荣, 2009. 花斑皮蠹成虫行为观察. 西北林学院学报, 24(2): 91–93.]
- Wilkins RV, Zhu KY, Campbell JF, Morrison WR, 2020. Mobility and dispersal of two cosmopolitan stored-product insects are adversely affected by long-lasting insecticide netting in a life stage-dependent manner. *Journal of Economic Entomology*, 113(4): 1768–1779.
- Zhao SR, Wang YG, Gao ZH, Bu SH, Lu XL, 2008. Biological characteristics of *Trogoderma variabile*. *Shaanxi Forest Science and Technology*, 36(2): 110–115. [赵姝荣, 王云果, 高智辉, 卜书海, 鲁晓琳, 2008. 花斑皮蠹生物学特性研究. 陕西林业科技, 36(2): 110–115.]