

中国棉铃虫七十年研究工作的回顾*

和 伟** 吴孔明***

(中国农业科学院植物保护研究所, 植物病虫害综合治理全国重点实验室, 北京 100193)

摘 要 棉铃虫 *Helicoverpa armigera* 是对全球农作物生产构成严重威胁的重大害虫, 本文回顾了中国 70 年来棉铃虫种群发生与危害动态及其生物学、生态学、监测预警与控制技术的研究进展。总体上, 中国棉铃虫在 20 世纪 50-70 年代处于轻度发生期、80-90 年代进入由化学农药抗性引起的重度发生阶段、2000 年以来下降到 Bt 棉花种植后的中度发生期。作为适宜半干旱地区环境发生的害虫, 棉铃虫在中国不同气候区域的发生规律和程度受作物品种和种植结构、温度和降雨等气候因素、自然天敌的丰富度以及农药使用等多种因素影响。棉铃虫分化出适应中国不同气候带的地理型, 结合东亚季风循环的气候特点, 形成了地理型-兼性迁飞的区域分布和转移危害模式。为保障国家农业健康发展, 中国构建了基于昆虫雷达和智能诱虫灯等信息技术的监测预警网络, 研发应用了基于 Bt 作物和生态调控的绿色防控技术体系, 为可持续控制棉铃虫的发生危害提供了重要科技支撑, 也为其它重大害虫的绿色防控提供了成功案例和可借鉴的经验。本文还展望了气候变化等因素对棉铃虫种群发生的潜在影响, 以及生物技术和人工智能技术发展对推动棉铃虫防控工作的作用。

关键词 棉铃虫; 发生动态; 监测预警; 绿色防控; Bt 作物

A review of 70 years of researches on cotton bollworm, *Helicoverpa armigera* in China

HE Wei** WU Kong-Ming***

(State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, CAAS, Beijing 100193, China)

Abstract The cotton bollworm, *Helicoverpa armigera* is a major pest that poses a serious threat to global crop production. This article reviews the population dynamics and damage caused by the pest in China over the past 70 years, as well as the research progress in its biology, ecology, monitoring and early warning, and control technologies. In general, the cotton bollworm in China was in a mild occurrence period from the 1950s to the 1970s, entered a severe occurrence stage caused by chemical pesticide resistance from the 1980s to the 1990s, and has declined to a moderate occurrence period after the planting of Bt cotton since 2000. As a pest suitable for semi-arid environments, the occurrence patterns and severity of the insect in different climate regions of China are influenced by various factors such as crop varieties and planting structures, temperature and rainfall, the richness of natural enemies, and pesticide use. The cotton bollworm has differentiated into geographical types adapted to different climate zones in China. Combined with the climatic characteristics of the East Asian monsoon circulation, it has formed a geographical type-facultative migratory regional distribution pattern. To ensure the healthy development of national agriculture, China has established a monitoring and early warning network based on information technologies such as insect radar and intelligent insect traps, and has developed and applied a green control technology system based on Bt crops and ecological regulation, providing important scientific and technological support for the sustainable control of its occurrence and damage, and also providing a successful case and referenceable experiences for the green control of other major pests. This article also looks forward to the potential impact of climate change and other factors on the population dynamics of the pest, as well as the role of biotechnology and artificial intelligence in its control.

Key words *Helicoverpa armigera*; occurrence dynamics; monitoring and early warning; green control; Bt crop

*资助项目 Supported project: 中国-东南亚空中廊道重大农业害虫跨境迁飞调查 (2023FY100500)

**第一作者 First author, E-mail: hewei6006@163.com

***通讯作者 Corresponding author, E-mail: wukongming@caas.cn

收稿日期 Received: 2025-07-29; 接受日期 Accepted: 2025-08-20

棉铃虫 *Helicoverpa armigera* 隶属鳞翅目 Lepidoptera 夜蛾科 Noctuidae, 是一种原生于旧大陆的世界性农业害虫 (Hardwick, 1965; 郭予元, 1998a; Tay *et al.*, 2013), 其适宜发生于年降雨量 400-800 mm 的半干旱地区, 在亚洲包括中国、印度、哈萨克斯坦、伊朗等国家 (Arnemann *et al.*, 2019), 在非洲分布在撒哈拉以南的大部分国家 (Karim, 2000; Sithanantham *et al.*, 2001), 在欧洲常见于南部和东南部地区 (Avilla and González-Zamora, 2010), 在大洋洲分布于澳大利亚和新西兰 (Zalucki and Furlong, 2005)。2013 年在南美洲的巴西首次记录棉铃虫为害后, 其迅速入侵巴西全境和邻国 (Murúa *et al.*, 2014; Sosa-Gómez *et al.*, 2016)。目前, 棉铃虫分布范围已扩展至南美洲的大部分地区, 虽未在北美洲定殖, 但仍有较高的入侵风险 (De Freitas Bueno *et al.*, 2015; Kriticos *et al.*, 2015; Riaz *et al.*, 2021)。

由于棉铃虫寄主作物种类丰富并具有远距离迁飞习性 (Fitt, 1989; Liu *et al.*, 2004; Jones *et al.*, 2015), 其常形成区域性灾变, 严重威胁世界各地棉花、玉米和豆类作物生产 (郭予元, 1998b; Oliveira *et al.*, 2014; Haile *et al.*, 2021)。中国棉铃虫的研究工作起步于 20 世纪 50 年代, 本文系统综述了过去 70 余年中国科学家对其发生规律、生物学行为、监测预警与防控技术的研究历程, 以期为中国其它重要农林害虫和全球棉铃虫的科学研究与防治工作提供借鉴。

1 中国棉铃虫发生与危害情况及影响因素

1.1 棉铃虫发生与危害的演变过程

新中国成立以来, 棉铃虫总体可分为 20 世纪 50-70 年代轻度发生、80-90 年代重度发生、2000 年以来中度发生三个阶段。20 世纪 50 年代棉铃虫在华北棉区局部严重发生, 但全国范围内整体危害较轻, 对棉花的危害程度低于棉蚜 *Aphis gossypii*、朱砂叶螨 *Tetranychus cinnabarinus* 和截形叶螨 *Tetranychus truncatus* (齐兆生和王德

秀, 1958), 但 60 年代中期以后, 逐渐发展为黄河流域和辽河特早熟棉区的主要害虫, 70 年代初期在黄河流域和长江流域局部地区严重发生 (姜玉英等, 2021); 80 年代初期生产上大量使用拟除虫菊酯防治棉铃虫, 遏制了棉铃虫严重发生的发展趋势, 但 80 年代中后期后棉铃虫对多种化学农药产生了抗性, 种群发生与危害程度明显加大。进入 90 年代后, 棉铃虫在全国范围内连年大暴发, 特别是 1992 年在山东、河南和河北等省的 4×10^6 hm² 棉田特大发生, 重灾区棉花减产超 50% 以上 (郭予元, 1998b); 1997 年黄河流域开始商业化种植转 *Bt-Cry1Ac* 基因抗虫棉花 (Bt 棉花), 到 2000 年黄河流域 Bt 棉花种植面积占棉花总面积 80% 以上 (吴孔明, 2020)。Bt 棉花的种植切断了棉铃虫在小麦、棉花、玉米和花生等寄主作物的季节性转移危害的链条, 有效控制了棉铃虫的发生与危害程度 (Wu *et al.*, 2008; Li *et al.*, 2020)。2010 年后, 随着 Bt 棉花在中国东部地区种植面积的下降和花生等作物种植面积的增加, 棉铃虫形成了小麦-花生-玉米的季节性转移危害链条, 整体发生趋势加重 (关秀敏等, 2016; 陆宴辉等, 2018; Xu *et al.*, 2025), 2023、2024 和 2025 年在全国发生面积分别为 7×10^6 、 6×10^6 和 3.333×10^6 hm² (刘杰等, 2023, 2024, 2025)。

1.2 棉铃虫发生的区域性特征

棉铃虫嗜好取食作物的繁殖器官和幼嫩的生长点, 中国不同气候带的生态环境和作物种植结构有较大的差别, 导致棉铃虫在不同区域的发生规律有较大的变化 (图 1)。在北部的寒温带地区基本没有棉铃虫发生, 但中温带地区棉铃虫 1 年发生 2-3 代, 第 1 代主要危害小麦穗部, 2-3 代主要危害棉花、大豆、玉米、花生等作物 (张福艳等, 2004)。暖温带地区, 棉铃虫 1 年可发生 3-4 代 (谢敬雪, 2010; 李耀发等, 2024)。第 1 代主要危害小麦, 2-4 代危害棉花、玉米、花生、大豆等 (陆宴辉等, 2018)。在北亚热带和中亚热带地区, 棉铃虫 1 年发生 5-6 代 (周柏龄, 2004), 第 1 代主要危害小麦、番茄、豌豆

等, 2-6 代主要危害棉花、玉米、大豆、花生、番茄、向日葵、辣椒等 (张玲和武向文, 2003; 唐于银等, 2008)。在南亚热带和热带地区, 最冷月平均气温在 10℃以上, 棉铃虫可完成周年

繁殖与危害, 一年发生 8-10 代 (郭予元, 1998b), 主要危害玉米、番茄、辣椒、大豆、花生、向日葵和棉花等作物。在西南的高原气候区, 由于寄主作物的缺乏, 棉铃虫发生的风险低、危害轻。



图 1 棉铃虫在中国不同气候带的发生代别与主要寄主作物种类

Fig. 1 Occurrence generation and main host crop types of *Helicoverpa armigera* in different climate zones of China

地图来源于国家基础地理信息中心, 审图号: 京审字 (2025) G 第 2152 号。图 2 同。

The map was sourced from the National Administration of Surveying, Mapping and Geoinformation, with the review approval number: JingShenZi (2025) G No. 2152. The same for Fig. 2.

1.3 影响棉铃虫发生程度的主要因素

棉铃虫的发生程度受作物品种、作物种植结构、气候因素、自然天敌的丰富度以及农药使用情况等多种因素的影响。传统的作物品种对棉铃虫抗性低, 但 Bt 作物是影响棉铃虫种群动态的重要因子 (Wu *et al.*, 2008)。高强度的降雨对

棉铃虫种群影响较大, 长江流域及以南地区夏季降雨多、土壤含水量高, 可显著增加蛹的死亡率。因此, 南方地区 7 月份之前的种群发生较轻, 往往在 8 月份以后的旱季发生严重 (郭予元, 1998b)。高温地区棉铃虫发生代别多, 冬季低温可显著降低越冬蛹种群数量。棉铃虫的自然天敌

种类丰富 (表 1), 天敌丰富度的增加可减少各虫态的种群密度 (徐永芝等, 2020)。化学农药亦是影响棉铃虫种群发生的重要因子, 农药可在短期内控制棉铃虫的发生, 但长期应用后抗药性的产生可显著减低控制效率, 其对天敌的杀伤作用还会引起种群的再猖獗 (郭予元, 1998b)。

表 1 棉铃虫的主要天敌种类与应用技术

Table 1 The main natural enemy types and application techniques of *Helicoverpa armigera*

科 Family	种 Species	特点与应用技术 Characteristics and application techniques	参考文献 References
茧蜂科 Braconidae	中红侧沟茧蜂 <i>Cotesia ruficrus</i>	幼虫寄生; 以低龄粘虫幼虫为寄主进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 寄生率 54.6%-62.87% Larvae parasitism; breeding with young larvae of <i>Mythimna separata</i> as the host; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; parasitism rate of 54.6%-62.87%	李建成等, 2010
姬蜂科 Ichneumonidae	棉铃虫齿唇姬蜂 <i>Campoletis chlorideae</i>	幼虫寄生; 以 2 龄棉铃虫幼虫为寄主进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 寄生率 19.2%-40.0% Larvae parasitism; breeding with second-instar <i>H. armigera</i> larvae as the host; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; parasitism rate of 19.2%-40.0%	罗梅浩等, 2005; 杨赛赛等, 2019
赤眼蜂科 Trichogrammatidae	螟黄赤眼蜂 <i>Trichogramma chilonis</i>	卵寄生; 以柞蚕卵作为寄主进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 寄生率 41.28%-83.40% Eggs parasitism; breeding with oak silkworm eggs as the host; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; parasitism rate of 41.28%-83.40%	李丽娟等, 2005
瓢虫科 Coccinellidae	龟纹瓢虫 <i>Propylaea japonica</i>	捕食卵和幼虫; 以人工饲料或蚜虫进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 日最大捕食 70 粒卵 Preying on eggs and larvae; reared on artificial diet or aphids; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; maximum daily predation of 70 eggs	高孝华和时爱菊, 2005; Li et al., 2021
	异色瓢虫 <i>Harmonia axyridis</i>	捕食卵和幼虫; 以人工饲料或蚜虫进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 具备较强捕食能力 Preying on eggs and larvae; reared on artificial diet or aphids; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; possessing strong predatory capacity	孙贝贝等, 2016; 李姝等, 2019
草蛉科 Chrysopidae	大草蛉 <i>Chrysoperla septempunctata</i>	捕食卵和幼虫; 以人工饲料进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 整个幼虫期可捕食幼虫 570 头 Preying on eggs and larvae; reared on artificial diet; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; during the entire larval stage, it preys on 570 larvae	武汉师范学院生物系天敌昆虫研究组, 1976; 张帆等, 2004
	中华草蛉 <i>Chrysopa sinica</i>	捕食卵和幼虫; 以人工饲料进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 整个幼虫期可捕食幼虫 574 头 Preying on eggs and larvae; reared on artificial diet; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; during the entire larval stage, it preys on 574 larvae	丁岩钦和陈玉平, 1986
蝽科 Pentatomidae	蝽蝽 <i>Arma chinensis</i>	捕食幼虫; 以黄粉虫蛹或人工饲料进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 田间防效 60%以上 Preying on larvae; reared using mealworm pupae or artificial diet; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; field control efficacy above 60%	肖雪庄等, 2023; 陈俊华等, 2025

续表 1 (Table 1 continued)

科 Family	种 Species	特点与应用技术 Characteristics and application techniques	参考文献 References
	叉角厉蝽 <i>Eocanthecona furcellata</i>	捕食幼虫; 以人工饲料进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 最大日捕食量 47 头幼虫 Preying on larvae; reared using artificial diet; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; maximum daily predation rate of 47 larvae	何旭诺等, 2013; 陈俊华等, 2024
花蝽科 Anthocoridae	小花蝽 <i>Orius</i> spp.	捕食卵和幼虫; 以人工饲料进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 田间防效 58.7%-80.6% Preying on eggs and larvae; reared using artificial diet; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; field control efficacy of 58.7%-80.6%	崔素贞, 1994; 刘文静等, 2010
蠼螋科 Labiduridae	蠼螋 <i>Labidura riparia</i>	捕食幼虫; 以人工饲料进行繁育; 棉铃虫发生初期或卵孵化盛期释放; 最大日捕食量 31 头幼虫 Preying on larvae; reared using artificial diet; releasing during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; maximum daily predation rate of 31 larvae	田彩虹等, 2023
杆状病毒科 Baculoviridae	棉铃虫核型多角体病毒 <i>Helicoverpa armigera</i> nucleopolyhedrovirus	毒杀幼虫; 已研发了高含量的病毒原粉和水分散粒剂等多种剂型产品; 棉铃虫发生初期或卵孵化盛期喷施; 田间防效 86%以上 Kill larvae; high-content virus original powder and water-dispersible granules and other formulations have been developed; spraying during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; field control efficacy above 86%	秦启联等, 2008; 魏周秀和刘小侠, 2020
白僵菌科 Clavicipitaceae	球孢白僵菌 <i>Beauveria bassiana</i>	毒杀幼虫; 已研发高毒力菌株、可湿性粉剂等多种剂型产品; 棉铃虫发生初期或卵孵化盛期喷施; 侵染后棉铃虫室内校正死亡率为 63% Kill larvae; highly virulent strains and wettable powder formulations have been developed; spraying during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; after infection, the corrected mortality rate of cotton bollworm in the laboratory is 63%	孙鲁娟等, 2001; 于健等, 2020
绿僵菌科 Clavicipitaceae	莱氏绿僵菌 <i>Metarhizium rileyi</i>	毒杀幼虫; 已研发高毒力菌株、颗粒剂等多种剂型产品; 棉铃虫发生初期或卵孵化盛期喷施; 侵染后棉铃虫室内校正死亡率为 73% Kill larvae; highly virulent strains and granule formulations have been developed; spraying during the early stage of infestation of <i>H. armigera</i> or at the peak of egg hatching; after infection, the corrected mortality rate of cotton bollworm in the laboratory is 73%	杨华等, 2015
芽孢杆菌科 Bacillaceae	苏云金芽孢杆菌 <i>Bacillus thuringiensis</i>	毒杀幼虫; 已研发出多种防治棉铃虫的 Bt 农药和 Bt 作物 (棉花、玉米、大豆), Bt 农药的控制效果 40%-70%, Bt 作物的防效可达 90%以上 Kill larvae; various Bt pesticides and Bt crops (cotton, corn, soybean) for controlling cotton bollworm have been developed; the control efficacy of Bt pesticides ranges from 40%-70%, while Bt crops can achieve a control efficacy of over 90%	Wang <i>et al.</i> , 2006; Wu <i>et al.</i> , 2008; Yang <i>et al.</i> , 2023

2 棉铃虫的生物学特征与适应性进化

棉铃虫的生态适应能力和进化潜力是其在

不同气候带广泛分布的生物学基础(图 2), 对其取食行为、繁殖行为、迁飞行为、生物型分化以及抗药性机制的深入研究有助于发展监测预警与综合防控策略。

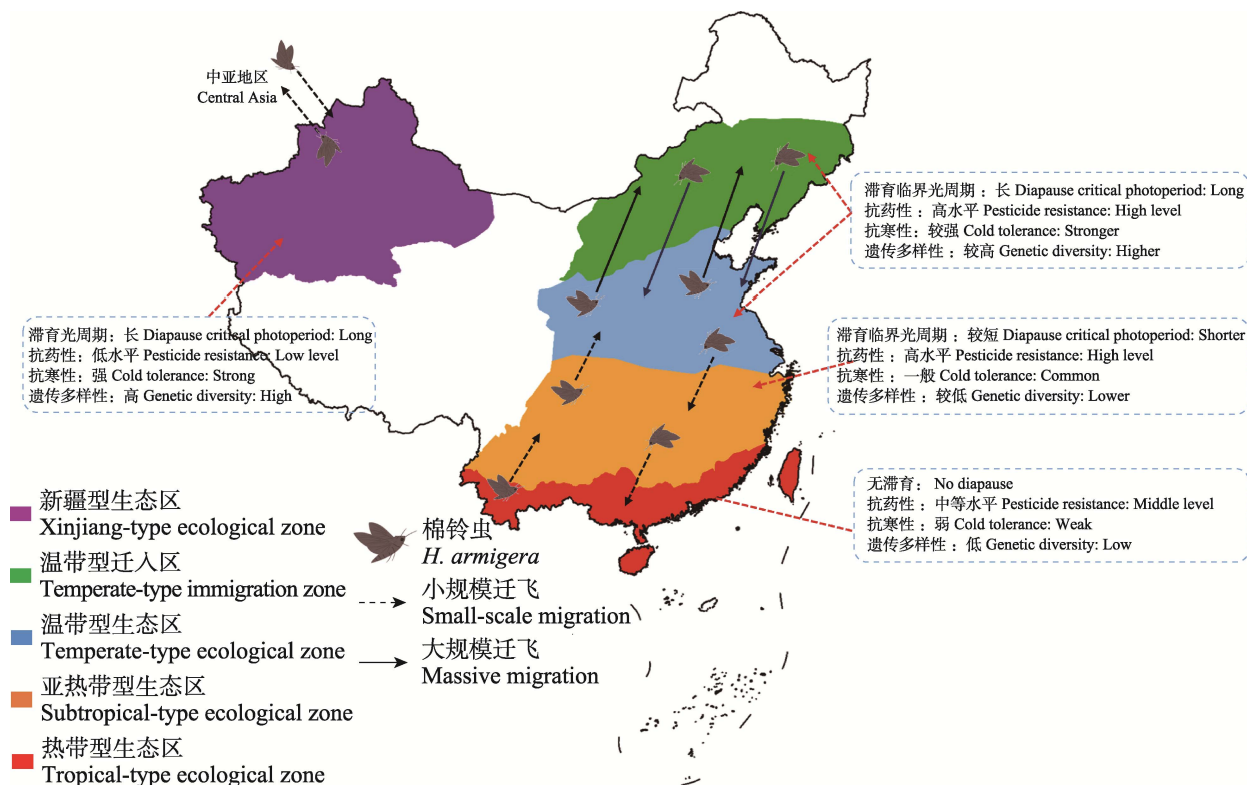


图 2 中国棉铃虫地理型的组成、环境适应性特征与迁飞特点

Fig. 2 Geo-type composition, environmental adaptability, and migration characteristics of *Helicoverpa armigera* in China

2.1 取食行为

棉铃虫的寄主植物有 30 余科 200 余种, 包括玉米、高粱、烟草、棉花、番茄、向日葵、大豆、油菜和花生等多种粮食与蔬菜作物(郭予元, 1998b)。幼虫具有自残习性, 自残行为主要发生在 3 龄以上阶段, 密度是产生自残行为的关键因素(Tang *et al.*, 2016)。幼虫的取食选择依靠口器外颚叶的两对栓锥感受器来感知味觉信息, 经过额神经节的处理, 传递至高级神经中枢来调控幼虫的行为(Tang *et al.*, 2000)。由于幼虫活动范围有限, 成虫的产卵选择决定了幼虫的取食植物。棉铃虫成虫羽化后, 为维持机体正常的发育、迁飞和繁殖行为, 需在蜜源植物上取食花蜜补充

营养(Zhou *et al.*, 2019b)。成虫一般在黄昏时将喙伸入花内吮食(郭予元, 1998b), 其具有灵敏的视觉和嗅觉, 依靠花香的气味、颜色、温湿度以及二氧化碳的浓度来定位蜜源植物(胡璞等, 2017; Zhang *et al.*, 2024; Chen *et al.*, 2025), 如成虫可通过花香中的苯乙醛、芳樟醇以及单萜烯类来识别定位寄主(吴孔明和郭予元, 2000b)。

2.2 繁殖行为

棉铃虫雌蛾通过释放微量的性信息素吸引雄蛾交配, 雄蛾通过触角上的嗅觉感器和性信息素受体来识别性信息素(Liu *et al.*, 2021)。雄蛾从 1 日龄起便可交配, 而雌蛾的交配始于 2-3

日龄, 交配高峰日为 4 日龄, 高峰期为凌晨 4:00-6:00 (李国清等, 1998)。雌蛾具有多次交配习性, 一生可交配 1-7 次。雌蛾交配后, 其寿命会显著缩短, 但成熟卵产出率会显著提高 (李国清等, 2002)。棉铃虫交配行为受光周期、光强度、温湿度和飞行等多种因素的影响, 如强光 (50 lx) 抑制雌蛾的求偶行为、性信息素合成以及交配, 微光 (0.5 lx) 促进了雌蛾的求偶、交配 (闫硕等, 2014)。在 14 L : 10 D 的光周期下, 棉铃虫成虫交配次数和交配率最高 (孙晓婷等, 2019)。雌蛾一生可产卵 1 000 粒左右, 在 25 °C 时, 雌蛾平均产卵量最大 (吴坤君等, 1978)。幼虫期的营养对其产卵量具有显著影响, 取食普通菜豆的棉铃虫产卵量显著高于取食玉米、棉花、番茄、辣椒和烟草 (Liu *et al.*, 2004)。

2.3 生态型分化

棉铃虫对环境的适应具有地域性和遗传稳定性, 已分化成不同的地理型。湖南衡阳和新疆哈密棉铃虫种群杂交和回交后代雌蛾产卵量、卵孵化率等繁殖参数无显著变化, 表明不同气候区棉铃虫遗传分化尚未达到亚种水平 (吴孔明和郭予元, 2007)。不同地理种群棉铃虫滞育诱导研究表明, 我国华南地区棉铃虫不具有或仅有很弱的滞育特性, 长江流域中下游南部地区棉铃虫具有较短的滞育诱导光周期, 而长江中下游地区北部、黄河流域棉区、北部特早熟棉区和西北内陆棉区的种群对光、温诱导的滞育反应则极为敏感 (吴孔明和郭予元, 1997, 2000c)。对各生态区棉铃虫滞育蛹过冷却点测定表明不同地理种群抗寒能力差异明显, 且随地理纬度和海拔升高过冷却点逐渐下降 (吴孔明等, 1997)。在土壤相对含水量 0%-80% 条件下, 不同地理种群的羽化率随土壤含水量增加而显著下降; 20-30 °C 温度区, 不同地理种群发育速度无显著分化现象 (吴孔明和郭予元, 2007)。基于环境适应性可将我国棉铃虫种群划分为热带型、亚热带型、温带型和新疆型, 它们的适生区分别是华南地区、长江中下游地区、黄河流域地区和新疆地区 (Wu and Guo, 2005)。棉铃虫群体基因组的测序结果表

明我国棉铃虫在遗传学层面可分为华南种群、华中-华北种群和新疆种群, 且新疆种群与中国其他地区种群基因组存在明显差异, 其对极端气候的适应性更强 (Jin *et al.*, 2023a)。

2.4 兼性迁飞行为

棉铃虫是兼性迁飞害虫, 成虫具备远距离迁飞能力。飞行磨室内吊飞试验表明, 成虫连续飞行 6 d 平均累计飞行时间为 41.30 h, 飞行距离为 239.70 km (吴孔明和郭予元, 1996)。在高空借助气流, 成虫飞行速度可达 21-41 km/h, 持续飞行时间可达 5-10 h (Feng *et al.*, 2005)。棉铃虫的迁飞是为了躲避不良环境, 寻找合适的栖息地, 食物、种群密度、气候因素是诱导棉铃虫迁飞的主要因子。棉铃虫的迁飞行为分为起飞、巡航、降落 3 个阶段, 起飞通常发生在黄昏时刻 (日落后 0.5 h), 而降落则在黎明时刻 (日出前 0.5 h) (Feng *et al.*, 2004)。成虫迁飞高度在距地面 1 500 m 以下, 虫群一般聚集在 200-500 m 左右形成高密度迁飞层, 在华北地区该高度区间内的温度、风速最适宜棉铃虫迁飞 (Feng *et al.*, 2009)。棉铃虫具有顺风定向习性, 在不同季节常借助不同高度层的有利风向, 实现远距离风载迁飞 (吴孔明和郭予元, 2007; Feng *et al.*, 2009)。在秋季回迁时, 棉铃虫会主动飞行至 500-1 500 m 高度以借助盛行的偏北风向南迁移。当风速较强且方向稳定时, 棉铃虫共同定向特性明显, 在雷达显示屏呈现哑铃型回波分布。棉铃虫的迁飞活动受温湿度、光周期等环境因素的显著影响, 在温度低于 13 °C 时停止飞行 (高月波和翟保平, 2010)。相比非迁飞个体, 迁飞棉铃虫体内能量代谢基因和飞行肌结构发育基因表达量差别明显, 且保幼激素合成减少 (Jones *et al.*, 2015)。温带型第 1-2 代棉铃虫可凭借其远距离迁飞能力在春、夏季从温带生态区北部地区大规模北迁至东北地区为害, 秋季从东北地区回迁至华北地区滞育越冬 (Feng *et al.*, 2009; Zhou *et al.*, 2019a)。由于南方夏季降雨量大导致种群密度低, 亚热带型和热带型棉铃虫难以随西南气流北迁, 但秋季种群可随风在相邻生态区迁移。新疆和内地之间的天然地形屏障阻碍了新疆型种群

与内地种群的迁飞交流, 但存在随大西洋季风与中亚地区种群迁飞交流的可能性。

2.5 抗药性演化

化学农药具有高效、低成本等优点, 是棉铃虫防控的重要手段, 但高强度的使用化学杀虫剂必然导致棉铃虫产生抗性。50-60 年代, 我国防治棉铃虫主要以有机氯杀虫剂为主, 60 年代后期对有机氯杀虫剂抗性日益增强 (孙耘芹, 1982)。70 年代后期主要以有机磷和氨基甲酸酯类杀虫剂防治棉铃虫, 抗药性也逐渐增强。80-90 年代, 拟除虫菊酯类农药被广泛使用于防控棉铃虫, 致使棉铃虫抗性突增, 对菊酯类农药达到中等至高抗水平 (谭维嘉和赵焕香, 1990; 吴益东等, 1995)。1994-1997 年环渤海湾地区 26 个棉铃虫种群对三氟氯氰菊酯、辛硫磷和硫丹均有高水平抗性 (吴孔明和郭予元, 2000a)。2011 年华北地区 14 个田间种群对氰戊菊酯等农药表现出极强的抗性, 但西北地区抗性水平较低 (Yang *et al.*, 2013)。2014-2019 年华北地区田间种群对辛硫磷表现出中等水平抗性, 对三氟氯氰菊酯表现出中等至高水平抗性, 对甲维盐表现出低至中等水平抗性 (胡红岩等, 2021)。目前, 一些地区棉铃虫对拟除虫菊酯类、有机磷类、氨基甲酸酯类、二酰胺类和有机氯类等均表现出较高抗性 (Wang *et al.*, 2021)。棉铃虫主要通过杀虫剂靶标位点相关基因突变和增加解毒酶的表达对杀虫剂产生抗性 (黄云等, 2022)。棉铃虫钠离子通道基因发生突变, 使拟除虫菊酯类杀虫剂无法有效结合靶标, 导致其对拟除虫菊酯类杀虫剂产生抗药性 (王桂荣等, 2004)。细胞色素 P450 (CYP450)、羧酸酯酶 (Carboxylesterase) 和谷胱甘肽 S-转移酶 (GSTs) 是棉铃虫体内重要的解毒酶, 它们可以代谢杀虫剂, 减少杀虫剂在昆虫体内的毒性 (Zhang *et al.*, 2022; Jin *et al.*, 2023b)。除对化学农药的抗性外, 棉铃虫对 Bt 蛋白也产生了抗性。1997-2006 年棉铃虫田间种群对 Bt 杀虫蛋白 Cry1Ac 的抗性监测表明田间种群对杀虫蛋白 Cry1Ac 仍然敏感 (Wu, 2007)。

自 2010 年以来, 黄河流域和长江流域棉区棉铃虫种群对 Cry1Ac 的敏感性显著下降, 而新疆棉区棉铃虫种群对 Cry1Ac 仍然敏感 (Zhang *et al.*, 2011, 2019; Jin *et al.*, 2015)。棉铃虫主要通过原毒素蛋白活化受阻、杀虫蛋白受体的突变或者表达量降低和免疫系统的调节来对 Bt 蛋白产生抗性, 如棉铃虫通过降低激活原毒素的胰蛋白酶基因 *HaTryR* 的表达来适应 Cry1Ac 毒素 (Liu *et al.*, 2014)。ATP 结合盒 (ATP-binding cassette, ABC) 转运蛋白基因 *HaABCC2* 和 *HaABCC3* 突变后, 棉铃虫对 Cry1Ac 毒素的抗性超过 15 000 倍 (Wang *et al.*, 2020)。目前, 我国棉铃虫种群对 Cry1Ac 的抗性处于早期抗性阶段, 但抗性治理不可忽视 (吴益东等, 2021)。针对棉铃虫对 Bt 棉花的抗性治理, 我国主要采用“自然庇护所策略”延缓抗性演化速度 (Wang *et al.*, 2019)。

3 棉铃虫的监测预警与防治技术

过去的 70 年, 中国棉铃虫经历了农业防治为主、化学农药防治为主和以 Bt 棉花防治为主的技术体系三个阶段, 目前正向基于新一代信息技术和生物技术的高质量监测预警与绿色防控技术体系发展 (图 3)。

3.1 监测预警技术

3.1.1 成虫监测预警技术 棉铃虫成虫种群的监测技术主要包括雷达监测、灯诱监测、卵巢解剖、性诱/食诱监测等方法 (He *et al.*, 2021)。雷达监测以回波探测高空飞行的棉铃虫体型参数 (振翅频率、体型、体重) 和飞行参数 (飞行时间、高度、速度、体轴朝向) 信息, 实现对其迁飞行为的实时感知 (Feng, 2025)。灯诱监测则基于成虫的趋光性, 对不同地区棉铃虫种群长期诱集, 以分析棉铃虫种群季节性和年际性动态 (Feng *et al.*, 2005)。卵巢解剖是基于雌蛾卵巢发育级别来推测棉铃虫种群的虫源性质并预测产卵动态。通常来说, 棉铃虫外地迁入种群大部分雌蛾卵巢发育已经成熟, 卵巢发育级别为 1 级

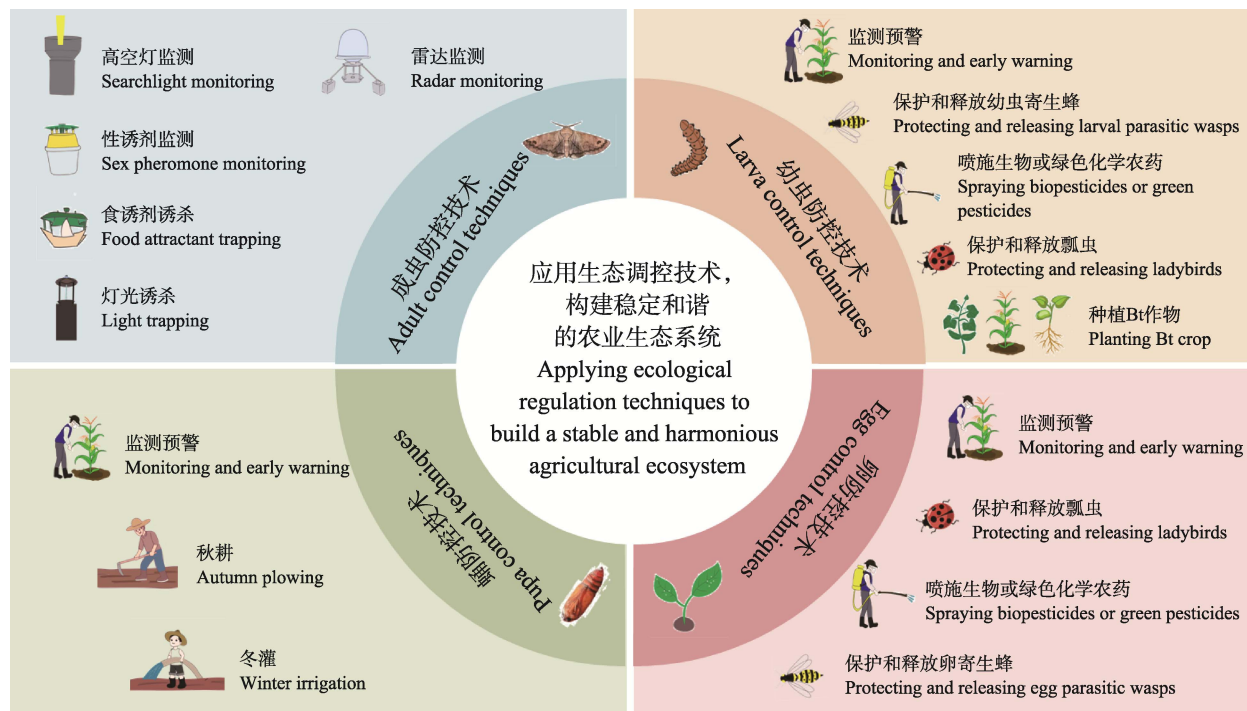


图3 棉铃虫早期监测预警与绿色防控技术体系架构

Fig. 3 The architecture of early monitoring and warning, and green control technology system for *Helicoverpa armigera*

的个体占比极低或不存在,而本地虫源 1-2 级的雌蛾占比较高(齐国君等, 2011)。性诱/食诱监测则利用性信息素或植物挥发物对田间成虫种群长期诱捕,分析不同地区棉铃虫种群发生规律。棉铃虫成虫的预警方法主要包括数理统计模型预测、迁飞轨迹预测和信息技术预测三个方面,如基于 12 年的黑光灯对棉铃虫种群动态监测数据和气象数据,利用 Single sine 模型预测了棉铃虫的羽化高峰期(马吉宏等, 2012);基于食诱剂对棉铃虫的田间监测数据,利用成虫日龄判定模型预测了棉铃虫成虫的羽化高峰期(He *et al.*, 2021);通过雷达和高空灯对棉铃虫高空飞行参数和种群动态的监测数据,运用轨迹分析模型预测了棉铃虫未来的迁飞路径和迁入地区(Feng *et al.*, 2009; Feng, 2025)。目前,我国已组建了由 43 个雷达组成的覆盖华南、西南、华北和东北地区昆虫雷达监测网络,极大提升了棉铃虫等重大农业迁飞害虫的监测预警能力。

3.1.2 卵、幼虫和蛹的田间发生测报技术 棉铃虫卵和幼虫的调查可采用棋盘式“W”形或对角线形 5 点取样法,重点调查寄主植物的嫩片、心

叶以及繁殖器官。越冬蛹的调查在冬前进行,采用 5 点取样法,每点检查 1 m² 寄主根部周围土壤。用泥刀或小铲子将 2-3 cm 深的土层挖向一侧,观察土壤表面是否有铅笔粗的圆形蛹道,若发现蛹道,则继续沿蛹道向下寻找蛹(姜玉英等, 2018)。卵、幼虫和蛹的测报技术包括发生期和发生量的预测,发生期预测通常以田间调查获得棉铃虫某一虫态的发育进度(始盛期、高峰期、盛末期),随后利用历期法、期距法、有效积温法去预测当代种群或下代种群某个虫态的发生时期。发生量预测基于棉铃虫历史虫情数据、气象数据等来预测卵和幼虫的发生量。随着信息技术在病虫害测报领域的应用,我国已建立“农作物重大病虫害数字化监测预警系统”,该系统可对不同地区棉铃虫的发生情况进行采集分析并实时监测预警(夏冰等, 2006)。

3.2 关键防治技术

3.2.1 Bt 作物防治技术 Bt 作物防治技术是指利用基因重组技术将来源于苏云金芽孢杆菌 *Bacillus thuringiensis* 的抗虫基因转入作物细胞

内, 使作物产生 Bt 毒素 (如 Cry1Ac) 来防治害虫。自中国 Bt 棉花商业化种植以来, Bt 棉花有效的控制了棉铃虫种群的发生 (Ouyang *et al.*, 2011)。近年来已开展了 Bt 玉米和 Bt 大豆防治棉铃虫的应用工作 (Yu *et al.*, 2013; Yang *et al.*, 2023)。

3.2.2 化学防治技术 针对棉铃虫的化学杀虫剂类型主要包括拟除虫菊酯类、有机磷类、氨基甲酸酯类、氨基甲酸酯类、双酰胺类、甲氨基阿维菌素苯甲酸、四氯虫酰胺等 (郭予元, 1998b)。可根据田间种群抗性监测结果调整用药, 交替使用不同作用机制的农药以减缓棉铃虫抗药性水平。除此之外, 还需科学用药, 减少农药的使用量, 提高农药的防治效率。使用无人机施药, 可喷洒均匀、精准施药, 减少农药的使用量降低防治成本 (高德良等, 2020)。

3.2.3 理化诱杀技术 棉铃虫的理化诱杀防治技术有灯光诱杀、糖醋液诱杀、机械捕杀、食诱剂诱杀等。基于棉铃虫的趋光性, 使用 LED 诱虫灯可大量诱杀成虫 (Pan *et al.*, 2020)。在烟田使用糖醋液配合诱捕器 1 d 可诱杀棉铃虫成虫 50 头以上, 烟草叶片受害率显著降低 (商胜华等, 2020)。大规模田间试验表明, 相比对照玉米田, 喷施混合微量杀虫剂的食诱剂 (植物源挥发物混合物) 玉米田棉铃虫幼虫的平均减少幅度为 34%-62% (Wang *et al.*, 2023)。

3.2.4 生物防治技术 棉铃虫的生物防控主要通过利用其天敌昆虫和微生物病原等生物资源来控制棉铃虫的种群数量, 减少对农作物的危害 (表 1)。在新疆南部棉区释放螟黄赤眼蜂 *Trichogramma chilonis* 对棉铃虫 2 代卵的累计寄生率为 18.67%-44.02%, 虫口减退率为 25.3%-64.2%, 蕾铃被害减退率为 46.8%-76.8% (许建军等, 2004)。施用棉铃虫核型多角体病毒 (HaNPV) 水分散剂 (6×10^{10} PIB/g) 7 和 10 d 后, 棉铃虫的田间防效分别为 68.3% 和 84.1% (陆宴辉等, 2020)。

3.2.5 农业防治技术 棉铃虫的农业防控措施主要包括秋耕冬灌压越低冬蛹基数; 推广抗虫品种, 调整作物布局, 如玉米和棉花等作物间作,

增加复种指数, 丰富天敌资源 (Zhang *et al.*, 2025); 增强田间管理, 推广促早栽培, 使秋季棉铃虫无适宜食物资源 (郭予元, 1998b)。

3.2.6 生态调控技术 棉铃虫生态调控技术是一种综合运用生态学原理和方法, 通过优化农田生态环境、保护和利用天敌、合理布局作物种植等方法来调控棉铃虫种群数量, 实现农业生态系统可持续发展的技术策略。如采用“推拉策略”在棉花上喷施印楝籽提取物 (NSKE) 驱赶棉铃虫, 在棉田种植诱集植物 (玉米和鸽豆) 吸引成虫产卵 (Zhang *et al.*, 2013)。在作物田周边或田埂种植蛇床子 *Cnidium monnieri*、金盏菊 *Calendula officinalis*、百日菊 *Zinnia elegans* 等功能植物, 为天敌昆虫 (如瓢虫、草蛉、食蚜蝇等) 提供食源或栖息地, 增强天敌对棉铃虫的控制能力 (陆宴辉等, 2020; 戈峰等, 2025)。

4 展望

棉铃虫毫无疑问是长期影响农业发展的重大害虫, 人类与它的斗争是复杂多变而永无止境的。未来的发展有挑战也有机遇, 一方面, 全球气候变化引起的温度升高、极端干旱和降雨的不确定性, 显著地扰乱了农业生态系统的平衡, 加大了棉铃虫的灾变风险 (Chen and Wu, 2024); 另一方面, 信息技术和生物技术的发展增加了棉铃虫监测预警与防控的技术手段, 如智能图像识别、卫星遥感、人工智能等提升了棉铃虫等害虫监测预警的高效化和智能化 (Wu *et al.*, 2022), 中国 Bt 抗虫作物技术已趋于成熟, 多个 Bt 抗虫玉米和 Bt 大豆品种已完成研发, 将在棉铃虫防控工作中发挥重大作用。RNA 干扰 (RNA interference, RNAi) 农药作为一种新型生物农药, 通过特异性抑制害虫关键基因表达, 可达到精准控制害虫的目的 (Fletcher *et al.*, 2020), 其具有精准防控、环境友好、不易产生抗性等优势, 符合可持续农业发展目标 (Jiang *et al.*, 2025)。目前, 已有一些鞘翅目害虫的 RNAi 农药产品市场化, 未来随着昆虫基因组学、纳米传递系统和生物信息学的进步, 针对棉铃虫等鳞翅目害虫的 RNAi 农药会进入生产应用阶段 (Duanmu *et al.*,

2025)。此外,棉铃虫是跨境迁飞害虫,东南亚、南亚国家丰富的寄主作物和周年适宜的气候环境形成了中国西南地区的虫源基地,应加强境外虫源监测和国际防控合作工作,构建棉铃虫防治的亚洲共同体(Zhou *et al.*, 2021)。

参考文献 (References)

- Armemann JA, Roxburgh S, Walsh T, Guedes J, Gordon K, Smagghe G, Tay WT, 2019. Multiple incursion pathways for *Helicoverpa armigera* in Brazil show its genetic diversity spreading in a connected world. *Scientific Reports*, 9(1): 19380.
- Avilla C, González-Zamora JE, 2010. Monitoring resistance of *Helicoverpa armigera* to different insecticides used in cotton in Spain. *Crop Protection*, 29(1): 100–103.
- Chen JH, Li FF, Du YQ, Xie JX, Zhang QQ, Wang CX, Guo SB, 2025. Predation ability and preference of *Arma chinensis* against *Helicoverpa armigera* larvae. *Journal of Henan Agricultural Sciences*, 54(1): 109–118. [陈俊华, 李非凡, 杜跃卿, 谢佳鑫, 张俏俏, 王晨旭, 郭世保, 2025. 蠋对棉铃虫幼虫的捕食能力及捕食偏好. 河南农业科学, 54(1): 109–118.]
- Chen JH, You WC, Xu MF, Chen YY, Lu M, Hou XF, Zhou Z, Liu HM, 2024. Predation ability and efficiency of *Eocanthecona furcellata* against *Helicoverpa armigera* larvae. *Journal of Southern Agriculture*, 55(12): 3507–3516. [陈俊华, 尤伟晨, 徐孟飞, 陈瑶瑶, 鲁锰, 侯鑫富, 周洲, 刘红敏, 2024. 叉角厉蝽对棉铃虫幼虫的捕食能力及捕食效率分析. 南方农业学报, 55(12): 3507–3516.]
- Chen JP, Wu KM, 2024. New plant protection: New challenge and new opportunity for plant protection. *New Plant Protection*, 1(1): e9.
- Chen QY, Chang HT, Ma BW, Guo MB, Cao S, Li B, Wang XQ, Berg B, Chu X, Zhang TT, Hansson B, Liu Y, Wang GR, 2025. Carbon dioxide drives oviposition in *Helicoverpa armigera*. *National Science Review*, Doi: 10.1093/nsr/nwaf270.
- Cui SZ, 1994. Studies on biological characteristics of *Orius minutus* and its control of major cotton insect pests. *Acta Gossypii Sinica*, 6(S1): 78–83. [崔素贞, 1994. 小花蝽生物学特性及其对主要棉虫控制作用的研究. 棉花学报, 6(S1): 78–83.]
- De Freitas Bueno A, Pomari-Fernandes A, Sosa-Gómez DR, 2015. *Helicoverpa armigera*: Current status and future perspectives in Brazil. *Current Agricultural Science and Technology*, 21(1): 1–7.
- Ding YQ, Chen YP, 1986. Predation pattern of the green lacewing, *Chrysoperla sinica* on cotton aphid and cotton bollworm. *Chinese Journal of Biological Control*, 2(3): 97–102. [丁岩钦, 陈玉平, 1986. 中华草蛉对棉蚜与棉铃虫的捕食作用研究. 生物防治通报, 2(3): 97–102.]
- Duanmu HN, Guo FY, Liu Y, He K, 2025. Developing RNAi pesticides in the post genomic era: A review. *Advanced Agrochem*, Doi: 10.1016/j.aac.2025.1007.1002.
- Feng HQ, 2025. First high-resolution vertical-looking radar for long-term automatic observation of high-flying insects in Asia. *Pest Management Science*, 81(7): 4072–4084.
- Feng HQ, Wu KM, Cheng DF, Guo YY, 2004. Northward migration of *Helicoverpa armigera* (Lepidoptera: Noctuidae) and other moths in early summer observed with radar in northern China. *Journal of Economic Entomology*, 97(6): 1874–1883.
- Feng HQ, Wu KM, Ni YX, Cheng DF, Guo YY, 2005. High-altitude windborne transport of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in mid-summer in northern China. *Journal of Insect Behavior*, 18(3): 335–349.
- Feng HQ, Wu XF, Wu B, Wu KM, 2009. Seasonal migration of *Helicoverpa armigera* (Lepidoptera: Noctuidae) over the Bohai Sea. *Journal of Economic Entomology*, 102(1): 95–104.
- Fitt GP, 1989. The ecology of *Heliothis* species in relation to agroecosystems. *Annual Review of Entomology*, 34: 17–53.
- Fletcher SJ, Reeves PT, Hoang BT, Mitter N, 2020. A perspective on RNAi-based biopesticides. *Frontiers in Plant Science*, 11: 51.
- Gao DL, Zhuang ZX, Song HW, Liu Y, Li LL, Zhang SC, 2020. Control effect of spraying insecticides by unmanned aerial vehicle against Lepidoptera pests in maize. *Shandong Agricultural Sciences*, 52(12): 103–107. [高德良, 庄占兴, 宋化稳, 刘钰, 李丽莉, 张思聪, 2020. 无人机喷施杀虫剂防治玉米鳞翅目害虫效果研究. 山东农业科学, 52(12): 103–107.]
- Gao XH, Shi AJ, 2005. Studies on the predatory function responses and searching efficiency of *Propylaea japonica* on eggs of *Helicoverpa armigera*. *Chinese Agricultural Science Bulletin*, 21(7): 346–348. [高孝华, 时爱菊, 2005. 龟纹瓢虫捕食棉铃虫卵的功能反应与寻找效应研究. 中国农学通报, 21(7): 346–348.]
- Gao YB, Zhai BP, 2010. Active temperature selection of flying *Helicoverpa armigera* (Lepidoptera: Noctuidae) moths. *Acta Entomologica Sinica*, 53(5): 540–548. [高月波, 翟保平, 2010. 飞行过程中棉铃虫对温度的主动选择. 昆虫学报, 53(5): 540–548.]
- Ge F, Liang XY, Zhang XR, Li Z, Ju Q, Ouyang F, Yang QF, Cai ZP, Su WW, Han GD, 2025. Ecologically based pest management mechanisms and practical applications of the functional plant *Cnidium monnieri*. *Chinese Journal of Applied Entomology*, 62(3): 559–566. [戈峰, 梁潇以, 张兴瑞, 李卓, 鞠倩, 欧阳芳, 杨泉峰, 蔡志平, 苏文雯, 韩国栋, 2025. 功能植物蛇床草生态控害作用及其应用. 应用昆虫学报, 62(3): 559–566.]

- Guan XM, Dong BX, Cao XR, Liu XS, Li ZB, Huang W, Zheng CM, Xu ZC, 2016. Impact of Bt cotton plantations on cotton bollworm populations in peanut fields. *Chinese Journal of Applied Entomology*, 53(4): 851–855. [关秀敏, 董保信, 曹欣然, 刘旬胜, 李振博, 黄渭, 郑成民, 徐兆春, 2016. 转基因抗虫棉种植面积变化对花生田棉铃虫种群影响. 应用昆虫学报, 53(4): 851–855.]
- Guo YY, 1998a. Research on Cotton Bollworm. Beijing: China Agriculture Press. 1–397. [郭予元, 1998a. 棉铃虫的研究. 北京: 中国农业出版社. 1–291.]
- Guo YY, 1998b. Reasons for the outbreak of the cotton bollworm and the trend prediction for 1998. *Journal of Plant Protection*, 24(2): 25–26. [郭予元, 1998b. 棉铃虫大发生原因和 1998 年发生趋势预测. 植物保护, 24(2): 25–26.]
- Haile F, Nowatzki T, Storer N, 2021. Overview of pest status, potential risk, and management considerations of *Helicoverpa armigera* (Lepidoptera: Noctuidae) for U.S. soybean production. *Journal of Integrated Pest Management*, 12: 3.
- Hardwick DF, 1965. The corn earworm complex. *Memoirs of the Entomological Society of Canada*, 97(S40): 5–247.
- He W, Zhao XC, Ali A, Ge SS, Zhang HW, He LM, Wu KM, 2021. Population dynamics and reproductive developmental analysis of *Helicoverpa armigera* (Lepidoptera: Noctuidae) trapped using food attractants in the field. *Journal of Economic Entomology*, 114(4): 1533–1541.
- He XN, Xian JD, Chen R, Zhang ZY, Zeng R, 2013. Effects of four insect feed on development and reproduction of *Cantheconidea furcellata* (Hemiptera: Asopinae). *Journal of Environmental Entomology*, 35(6): 799–803. [何旭诺, 冼继东, 陈然, 张拯研, 曾嵘, 2013. 4 种昆虫饲料对叉角厉蝽生长发育和繁殖的影响. 环境昆虫学报, 35(6): 799–803.]
- Hu HY, Ren XL, Ma XY, Ma YJ, Song XP, Wang D, Li HH, Ma Y, 2021. Resistance monitoring of cotton bollworm *Helicoverpa armigera* to three insecticides in northern China. *Journal of Plant Protection*, 48(4): 900–906. [胡红岩, 任相亮, 马小艳, 马亚杰, 宋贤鹏, 王丹, 李欢欢, 马艳, 2021. 华北棉区棉铃虫对三种杀虫剂的抗性监测. 植物保护学报, 48(4): 900–906.]
- Hu P, Zhao Q, Yuan MZ, Liu ZJ, Wang GP, Guo XR, Yuan GH, Li WZ, 2017. Progress in floral foraging cues used by anthophilous insects. *Journal of Entomological Research in Central China*, 13: 52–62. [胡璞, 赵琦, 原明珠, 刘紫晶, 王高平, 郭线茹, 原国辉, 李为争, 2017. 喜花昆虫访花利用的信息研究进展. 华中昆虫研究, 13: 52–62.]
- Huang Y, Wu PZ, Zheng JY, Zhang Y, Qiu LH, 2022. Status of resistance to chemical insecticides in cotton bollworm *Helicoverpa armigera* and research progresses on the molecular mechanisms. *Journal of Plant Protection*, 49(1): 336–350. [黄云, 吴沛卓, 郑钧月, 张瑜, 邱立红, 2022. 棉铃虫对化学杀虫剂的抗性现状及分子机制研究进展. 植物保护学报, 49(1): 336–350.]
- Jiang MM, Zhang Y, Chen CM, He LD, Li SC, 2025. Management of *Helicoverpa armigera* via plant-mediated RNA interference, progresses and challenges. *Crop Protection*, 190: 107101.
- Jiang YY, Liu J, Zeng J, Xia B, Lu YH, 2021. Monitoring and forecast of cotton pests in China: A review over the past 70 years. *Journal of Plant Protection*, 48(5): 940–946. [姜玉英, 刘杰, 曾娟, 夏冰, 陆宴辉, 2021. 中国棉花害虫测报: 70 年回顾. 植物保护学报, 48(5): 940–946.]
- Jiang YY, Liu J, Zeng J, Yang QP, Lu YH, 2018. Investigation and forecasting techniques for the cotton bollworm. *Chinese Journal of Applied Entomology*, 55(1): 132–137. [姜玉英, 刘杰, 曾娟, 杨清坡, 陆宴辉, 2018. 棉铃虫种群调查及测报技术. 应用昆虫学报, 55(1): 132–137.]
- Jin L, Zhang HN, Lu YH, Yang YH, Wu KM, Tabashnik BE, Wu YD, 2015. Large-scale test of the natural refuge strategy for delaying insect resistance to transgenic Bt crops. *Nature Biotechnology*, 33(2): 169–174.
- Jin MH, North HL, Peng Y, Liu HW, Liu B, Pan RQ, Zhou Y, Zheng WG, Liu KY, Yang B, Zhang L, Xu Q, Elfekih S, Valencia-Montoya WA, Walsh T, Cui P, Zhou YF, Wilson K, Jiggins C, Wu KM, Xiao YT, 2023a. Adaptive evolution to the natural and anthropogenic environment in a global invasive crop pest, the cotton bollworm. *The Innovation*, 4(4): 100454.
- Jin MH, Peng Y, Peng J, Zhang HH, Shan YX, Liu KY, Xiao YT, 2023b. Transcriptional regulation and overexpression of GST cluster enhances pesticide resistance in the cotton bollworm, *Helicoverpa armigera* (Lepidoptera: Noctuidae). *Communications Biology*, 6(1): 1064.
- Jones CM, Papanicolaou A, Mironidis GK, Vontas J, Yang YH, Lim KS, Oakeshott JG, Bass C, Chapman JW, 2015. Genomewide transcriptional signatures of migratory flight activity in a globally invasive insect pest. *Molecular Ecology*, 24(19): 4901–4911.
- Karim S, 2000. Management of *Helicoverpa armigera*: A review and prospectus for Pakistan. *Pakistan Journal of Biological Sciences*, 3(8): 1213–1222.
- Kriticos DJ, Ota N, Hutchison WD, Beddow J, Walsh T, Tay WT, Borchert DM, Paula-Moraes SV, Czapak C, Zalucki MP, 2015. The potential distribution of invading *Helicoverpa armigera* in North America: Is it just a matter of time? *PLoS ONE*, 10(3): 1–11.

- e0119618.
- Li DC, Chen P, Liu J, Chi BJ, Zhang XP, Liu YJ, 2021. Artificial rearing of the ladybird *Propylea japonica* on a diet containing oriental armyworm, *Mythimna separata*. *Entomologia Experimentalis et Applicata*, 169(5): 472–479.
- Li GQ, Chen CK, Han ZJ, Wang YC, 1998. Sex maturity and mating habits of *Helicoverpa armigera* (Hübner). *Journal of Nanjing Agricultural University*, 21(2): 42–46. [李国清, 陈长琨, 韩召军, 王荫长, 1998. 棉铃虫蛾性成熟与交配习性的研究. 南京农业大学学报, 21(2): 42–46.]
- Li GQ, Mu LL, Han ZJ, 2002. Effects of mating on female's reproduction in *Helicoverpa armigera*. *Journal of Nanjing Agricultural University*, 25(1): 27–30. [李国清, 慕莉莉, 韩召军, 2002. 交配对棉铃虫雌蛾生殖的调控. 南京农业大学学报, 25(1): 27–30.]
- Li JC, Lu ZY, Qu ZG, Liu WX, 2010. Research progress of *Microplitis mediator* and its application. *Journal of Hebei Agricultural Sciences*, 14(8): 4–11. [李建成, 路子云, 屈振刚, 刘文旭, 2010. 中红侧沟茧蜂研究及应用进展. 河北农业科学, 14(8): 4–11.]
- Li LJ, Lu X, Liu HW, Wang YZ, Zhang GH, Ding Y, 2005. Research progress on the artificial propagation and application technology of *Trichogramma chilonis*. *Journal of Jilin Agricultural Sciences*, 30(3): 23–28. [李丽娟, 鲁新, 刘宏伟, 汪洋洲, 张国红, 丁岩, 2005. 螟黄赤眼蜂人工繁殖与应用技术的研究进展. 吉林农业科学, 30(3): 23–28.]
- Li S, Wang J, Guo XJ, Tian RB, Wang S, Zhang F, 2019. Research progress and prospects of *Chrysopa pallens* (Rambur) (Hemiptera: Chrysopidae). *Journal of Environmental Entomology*, 41(2): 241–252. [李姝, 王杰, 郭晓军, 田仁斌, 王甦, 张帆, 2019. 天敌昆虫大草蛉的研究进展与展望. 环境昆虫学报, 41(2): 241–252.]
- Li WJ, Wang LL, Jaworski CC, Yang F, Liu B, Jiang YY, Lu YH, Wu KM, Desneux N, 2020. The outbreaks of nontarget mirid bugs promote arthropod pest suppression in Bt cotton agroecosystems. *Plant Biotechnology Journal*, 18(2): 322–324.
- Li YF, An JJ, Dou YN, Zhang SQ, Dang ZH, Li MY, Yuan WL, Guo JL, Gao ZL, 2024. Population distribution of *Helicoverpa armigera* in different geographical regions of Hebei Province. *Journal of Hebei Agricultural Sciences*, 28(1): 60–65. [李耀发, 安静杰, 窦亚楠, 张尚卿, 党志红, 李明远, 袁文龙, 郭江龙, 高占林, 2024. 河北省不同地理区域的棉铃虫种群分布. 河北农业科学, 28(1): 60–65.]
- Liu CX, Xiao YT, Li XC, Oppert B, Tabashnik BE, Wu KM, 2014. Cis-mediated down-regulation of a trypsin gene associated with Bt resistance in cotton bollworm. *Scientific Reports*, 4: 7219.
- Liu J, Bian Y, Zhang YY, Meng ZH, Huang C, Zeng J, 2025. Trends and causes of major crop pest and disease occurrences in China in 2025. *China Plant Protection*, 45(2): 26–29, 44. [刘杰, 卞悦, 张熠场, 孟泽华, 黄冲, 曾娟, 2025. 2025 年全国主要农作物重大病虫害发生趋势及其原因分析. 中国植保导刊, 45(2): 26–29, 44.]
- Liu J, Zeng J, Huang C, Bian Y, Zhang YY, Yang QP, 2024. Forecast of major crop pest and disease occurrence trends in China in 2024. *China Plant Protection*, 44(1): 37–40. [刘杰, 曾娟, 黄冲, 卞悦, 张熠场, 杨清坡, 2024. 2024 年全国农作物重大病虫害发生趋势预报. 中国植保导刊, 44(1): 37–40.]
- Liu J, Zeng J, Yang QP, Bian Y, Zhang YY, Huang C, 2023. Forecast of major crop pest and disease occurrence trends in 2023. *China Plant Protection*, 43(1): 32–35. [刘杰, 曾娟, 杨清坡, 卞悦, 张熠场, 黄冲, 2023. 2023 年农作物重大病虫害发生趋势预报. 中国植保导刊, 43(1): 32–35.]
- Liu S, Li B, Liu W, Liu Y, Ren BZ, Wang GR, 2021. Sex peptide receptor mediates the post-mating switch in *Helicoverpa armigera* (Lepidoptera: Noctuidae) female reproductive behavior. *Pest Management Science*, 77(7): 3427–3435.
- Liu WJ, Yu Y, Xu HF, Zhang AS, Men XY, Li LL, Zhang SC, 2010. Research progress on the artificial propagation of *Orius minutus*. *Shandong Agricultural Sciences*, 42(9): 83–88. [刘文静, 于毅, 徐洪富, 张安盛, 门兴元, 李丽莉, 张思聪, 2010. 小花蝽人工繁殖研究进展. 山东农业科学, 42(9): 83–88.]
- Liu ZD, Li DM, Gong PY, Wu KJ, 2004. Life table studies of the cotton bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), on different host plants. *Environmental Entomology*, 33(6): 1570–1576.
- Lu YH, Jiang YY, Liu J, Zeng J, Yang XM, Wu KM, 2018. Adjustment of cropping structure increases the risk of cotton bollworm outbreaks in China. *Chinese Journal of Applied Entomology*, 55(1): 19–24. [陆宴辉, 姜玉英, 刘杰, 曾娟, 杨现明, 吴孔明, 2018. 种植业结构调整增加棉铃虫的灾变风险. 应用昆虫学报, 55(1): 19–24.]
- Lu YH, Liang GM, Zhang YJ, Yang XM, 2020. Advances in the management of insect pests of cotton in China since the 21st century. *Chinese Journal of Applied Entomology*, 57(3): 477–490. [陆宴辉, 梁革梅, 张永军, 杨现明, 2020. 二十一世纪以来棉花害虫治理成就与展望. 应用昆虫学报, 57(3): 477–490.]
- Luo MH, Song N, Guo XR, Liu XG, Zhao GQ, 2005. Research progress in *Campoletis chorideae* Uchida. *Journal of Anhui Agricultural Sciences*, 33(12): 2388–2389, 2423. [罗梅浩, 宋南, 郭线茹, 刘晓光, 赵国强, 2005. 棉铃虫齿唇姬蜂研究概况.

- 安徽农业科学, 33(12): 2388–2389, 2423.]
- Ma JH, Lü ZZ, Liu YJ, Zhang J, Gao GZ, Xia DP, 2012. A method for reducing error in estimating the effective accumulated temperature of the *Helicoverpa armigera* eclosion peak. *Chinese Journal of Applied Entomology*, 49(4): 874–881. [马吉宏, 吕昭智, 刘永建, 张娟, 高桂珍, 夏德萍, 2012. 棉铃虫羽化高峰期有效积温预测法的校正. 应用昆虫学报, 49(4): 874–881.]
- Murúa MG, Scalora FS, Navarro FR, Cazado LE, Casmuz A, Villagrán ME, Lobos E, Gastaminza G, 2014. First record of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Argentina. *Florida Entomologist*, 97(2): 854–856.
- Oliveira CM, Auad AM, Mendes SM, Frizzas MR, 2014. Crop losses and the economic impact of insect pests on Brazilian agriculture. *Crop Protection*, 56: 50–54.
- Ouyang F, Liu ZD, Yin J, Su JW, Wang CZ, Ge F, 2011. Effects of transgenic Bt cotton on overwintering characteristics and survival of *Helicoverpa armigera*. *Journal of Insect Physiology*, 57(1): 153–160.
- Pan HS, Xu YL, Liang GM, Wyckhuys KAG, Yang YZ, Lu YH, 2020. Field evaluation of light-emitting diodes to trap the cotton bollworm, *Helicoverpa armigera*. *Crop Protection*, 137: 105267.
- Qi GJ, Lu F, Hu G, Wang FY, Gao Y, Lü LH, 2011. The application of ovarian dissection in the research on migratory insects in China. *China Plant Protection*, 31(7): 18–22. [齐国君, 芦芳, 胡高, 王凤英, 高燕, 吕利华, 2011. 卵巢解剖在我国迁飞昆虫研究中的应用. 中国植保导刊, 31(7): 18–22.]
- Qi ZS, Wang DX, 1958. Draft and explanation of the comprehensive pest control technical outline for the northern cotton-growing region. *Scientia Agricultura Sinica*, 62(5): 244–245. [齐兆生, 王德秀, 1958. 北部棉区大面积彻底防治棉虫技术纲要(草稿)及说明. 中国农业科学, 62(5): 244–245.]
- Qin QL, Cheng QQ, Zheng JF, Chen XZ, Zhang ST, Li X, Miao L, Zhang H, 2008. Production and application of *Helicoverpa armigera* nucleopolyhedrovirus bio-pesticides trademarked Keyun on large scale. *Biotechnology Bulletin*, 24(S1): 467–470. [秦启联, 程清泉, 郑建峰, 陈新中, 张松涛, 李瑄, 苗麟, 张寰, 2008. 科云牌棉铃虫核型多角体病毒生物农药的规模化生产和应用. 生物技术通报, 24(S1): 467–470.]
- Research Group of Pest Natural Enemies, Department of Biology, Wuhan Teachers College, 1976. Studies on green lacewings (*Chrysopa* spp.) and their use in biological control. *Acta Entomologica Sinica*, 19(3): 309–317. [武汉师范学院生物系天敌昆虫研究组, 1976. 草蛉幼虫对棉花害虫的捕食能力及食物对其个体发育的影响. 昆虫学报, 19(3): 309–317.]
- Riaz S, Johnson JB, Ahmad M, Fitt GP, Naiker M, 2021. A review on biological interactions and management of the cotton bollworm, *Helicoverpa armigera* (Lepidoptera: Noctuidae). *Journal of Applied Entomology*, 145(6): 467–498.
- Shang SH, Tian TA, Zhao L, Yu XF, Shen XX, Yang MF, 2020. Tobacco pests trapping and killing by sugar-acetic acid mixtures. *Tobacco Science & Technology*, 53(7): 26–32. [商胜华, 田太安, 赵丽, 于晓飞, 申修贤, 杨茂发, 2020. 不同配方糖醋液诱源对贵州遵义烟田害虫的诱杀作用. 烟草科技, 53(7): 26–32.]
- Sithanantham S, Abera TH, Baumgärtner J, Hassan SA, Löhr B, Monje JC, Overholt WA, Paul AVN, Wan FH, Zebitz CPW, 2001. EGG parasitoids for augmentative biological control of lepidopteran vegetable pests in Africa: Research status and needs. *International Journal of Tropical Insect Science*, 21(3): 189–205.
- Sosa-Gómez DR, Specht A, Paula-Moraes SV, Lopes-Lima A, Yano SAC, Micheli A, Morais EGF, Gallo P, Pereira PRVS, Salvadori JR, Botton M, Zenker MM, Azevedo-Filho WS, 2016. Timeline and geographical distribution of *Helicoverpa armigera* (Hübner) (Lepidoptera, Noctuidae: Heliethinae) in Brazil. *Revista Brasileira de Entomologia*, 60(1): 101–104.
- Sun BB, Yin Z, Hou ZR, Li JP, 2016. Progress on artificial breeding and application of *Harmonia axyridis*. *Current Biotechnology*, 6(2): 141–145. [孙贝贝, 尹哲, 侯峥嵘, 李金萍, 2016. 异色瓢虫人工繁育与应用进展. 生物技术进展, 6(2): 141–145.]
- Sun LJ, Wu KM, Guo YY, 2001. The pathogenicity of *Beauveria bassiana* to *Helicoverpa armigera* under different temperatures and humidities. *Acta Entomologica Sinica*, 44(4): 501–506. [孙鲁娟, 吴孔明, 郭予元, 2001. 不同温、湿度下白僵菌对棉铃虫幼虫的致病力. 昆虫学报, 44(4): 501–506.]
- Sun XT, Xu RB, Ge SS, Fu XW, Zhao XC, Wu KM, 2019. Effects of photoperiod on the eclosion, reproduction and flight performance of *Helicoverpa armigera* (Lepidoptera: Noctuidae). *Journal of Environmental Entomology*, 41(5): 1045–1056. [孙晓婷, 徐瑞斌, 葛世帅, 付晓伟, 赵新成, 吴孔明, 2019. 光周期对棉铃虫羽化、生殖和飞行的影响. 环境昆虫学报, 41(5): 1045–1056.]
- Sun YC, 1982. Pest resistance: II. Methods for detecting cotton bollworm resistance. *Entomological Knowledge*, 19(2): 46–47. [孙耘芹, 1982. 害虫的抗药性: II. 侦测棉铃虫抗药性的方法. 昆虫知识, 19(2): 46–47.]
- Tan WJ, Zhao HX, 1990. Changes of sensitivity of cotton bollworms feeding on different host plants to decamethrin. *Acta Entomologica Sinica*, 33(2): 155–160. [谭维嘉, 赵焕香, 1990. 取食不同寄主植物的棉铃虫对溴氰菊酯敏感性的变化. 昆虫学报, 33(2): 155–160.]

- Tang D, Wang C, Luo L, Qin J, 2000. Comparative study on the responses of maxillary sensilla styloconica of cotton bollworm *Helicoverpa armigera* and oriental tobacco budworm *H. assulta* larvae to phytochemicals. *Science China Life Sciences*, 43(6): 606–612.
- Tang T, Zhao CQ, Xu L, Qiu LH, 2016. Factors affecting larval cannibalism in the cotton bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae). *Oriental Insects*, 50(1): 23–33.
- Tang YY, Xu WH, Liu B, Wang RM, 2008. Development and improvement on comprehensive control technology cotton bollworm in Jiangsu coastal area. *Acta Agriculturae Jiangxi*, 20(6): 69–71. [唐于银, 徐文华, 刘标, 王瑞明, 2008. 江苏沿海棉区棉铃虫综合治理技术的发展与改进. 江西农业学报, 20(6): 69–71.]
- Tay WT, Soria MF, Walsh T, Thomazoni D, Silvie P, Behere GT, Anderson C, Downes S, 2013. A brave new world for an old world pest: *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Brazil. *PLoS ONE*, 8(11): e80134.
- Tian CH, Zhang JY, Xu CY, Li GP, Huang JR, Liu Y, Wang GS, Feng HY, Yin XM, Feng HQ, 2023. Predation capacity of *Labidura riparia* Pallas against *Helicoverpa armigera* (Hübner). *Plant Protection*, 49(1): 157–163. [田彩红, 张俊逸, 徐存翊, 李国平, 黄建荣, 刘毅, 王根松, 封洪云, 尹新明, 封洪强, 2023. 溪岸蠼螋对棉铃虫的捕食能力. 植物保护, 49(1): 157–163.]
- Wang GJ, Zhang J, Song FP, Wu J, Feng SL, Huang DF, 2006. Engineered *Bacillus thuringiensis* GO33A with broad insecticidal activity against lepidopteran and coleopteran pests. *Applied Microbiology and Biotechnology*, 72(5): 924–930.
- Wang GR, Xu G, Tan WJ, Wu KM, Guo YY, 2004. Novel mutation in the para-homologous sodium channel gene associated with nerve insensitivity resistance to pyrethroid in *Helicoverpa armigera*. *Chinese Journal of Applied and Environmental Biology*, 10(3): 332–336. [王桂荣, 徐广, 谭维嘉, 吴孔明, 郭予元, 2004. 菊酯类杀虫剂抗性棉铃虫 para 型钠离子通道基因的部分序列测定与突变. 应用与环境生物学报, 10(3): 332–336.]
- Wang J, Ma HH, Zhao S, Huang JL, Yang YH, Tabashnik BE, Wu YD, 2020. Functional redundancy of two ABC transporter proteins in mediating toxicity of *Bacillus thuringiensis* to cotton bollworm. *Public Library of Science Pathogens*, 16(3): e1008427.
- Wang LY, He LM, Zhu XM, Zhang JW, Li N, Fan JF, Li HF, Sun XJ, Zhang LJ, Lin YL, Wu KM, 2023. Large-area field application confirms the effectiveness of toxicant-infused bait for managing *Helicoverpa armigera* (Hübner) in maize fields. *Pest Management Science*, 79(12): 5405–5417.
- Wang PP, Ma JH, Head GP, Xia DP, Li J, Wang HQ, Yang ML, Xie ZM, Zalucki MP, Lu ZZ, 2019. Susceptibility of *Helicoverpa armigera* to two Bt toxins, Cry1Ac and Cry2Ab, in northwestern China: Toward developing an IRM strategy. *Journal of Pest Science*, 92(2): 923–931.
- Wang QQ, Rui CH, Wang L, Nahiyoon SA, Huang WL, Zhu JS, Ji XJ, Yang QJ, Yuan HZ, Cui L, 2021. Field-evolved resistance to 11 insecticides and the mechanisms involved in *Helicoverpa armigera* (Lepidoptera: Noctuidae). *Pest Management Science*, 77(11): 5086–5095.
- Wei ZX, Liu XX, 2020. Field efficacy trial of nuclear polyhedrosis virus (NPV) for controlling *Helicoverpa armigera* larvae in seed corn fields. *Agricultural Science-Technology and Information*, 2020(11): 9–10. [魏周秀, 刘小侠, 2020. 棉铃虫核型多角体病毒(NPV)防治制种玉米棉铃虫幼虫田间药效试验. 农业科技与信息, 2020(11): 9–10.]
- Wu KJ, Chen YP, Li MH, 1978. Life tables for experimental populations of the cotton bollworm, *Helicoverpa armigera* (Hübner), at different temperatures. *Acta Entomologica Sinica*, 21(4): 385–392. [吴坤君, 陈玉平, 李明辉, 1978. 不同温度下的棉铃虫实验种群生命表. 昆虫学报, 21(4): 385–392.]
- Wu KM, 2007. Monitoring and management strategy for *Helicoverpa armigera* resistance to Bt cotton in China. *Journal of Invertebrate Pathology*, 95(3): 220–223.
- Wu KM, 2020. Management strategies of fall armyworm (*Spodoptera frugiperda*) in China. *Plant Protection*, 46(2): 1–5. [吴孔明, 2020. 中国草地贪夜蛾的防控策略. 植物保护, 46(2): 1–5.]
- Wu KM, Guo YY, 1996. Flight activity in *Helicoverpa armigera*. *Acta Ecologica Sinica*, 16(6): 612–617. [吴孔明, 郭予元, 1996. 棉铃虫的飞翔活动. 生态学报, 16(6): 612–617.]
- Wu KM, Guo YY, 1997. Investigations on the migration and diapause in *Helicoverpa armigera*——diapause responses of different geographical populations of cotton bollworm *Helicoverpa armigera* Hübner. *Scientia Agricultura Sinica*, 30(3): 1–6. [吴孔明, 郭予元, 1997. 棉铃虫迁飞与滞育的研究——我国各棉区棉铃虫滞育诱导的光温反应特点. 中国农业科学, 30(3): 1–6.]
- Wu KM, Guo YY, 2000a. The coordinated development and analysis of contributing factors of cotton bollworm resistance to insecticides in round Bohai bay region. *Acta Phytophylacica Sinica*, 27(2): 173–178. [吴孔明, 郭予元, 2000a. 环渤海湾地区棉铃虫的抗药性水平及成因分析. 植物保护学报, 27(2):

- 173–178.]
- Wu KM, Guo YY, 2000b. Main achievements and prospects of cotton pest research in China in the 20th century. *Entomological Knowledge*, 37(1): 45–49. [吴孔明, 郭予元, 2000b. 我国 20 世纪棉花害虫研究的主要成就及展望. 昆虫知识, 37(1): 45–49.]
- Wu KM, Guo YY, 2000c. On the cold hardiness of cotton bollworm populations from Xinjiang uygur autonomous region. *Acta Phytophylacica Sinica*, 27(1): 23–26. [吴孔明, 郭予元, 2000c. 新疆棉铃虫的抗寒性研究. 植物保护学报, 27(1): 23–26.]
- Wu KM, Guo YY, 2005. The evolution of cotton pest management practices in China. *Annual Review of Entomology*, 50: 31–52.
- Wu KM, Guo YY, 2007. Geotype differentiation and regional migratory regularity of *Helicoverpa armigera* in China. *Plant Protection*, 33(5): 6–11. [吴孔明, 郭予元, 2007. 棉铃虫种群的地理型分化和区域性迁飞规律. 植物保护, 33(5): 6–11.]
- Wu KM, Guo YY, Wei JF, Sun FZ, 1997. On the cold hardiness of cotton bollworm *Helicoverpa armigera* (Hübner). *Acta Ecologica Sinica*, 17(3): 298–302. [吴孔明, 郭予元, 韦建福, 孙福在, 1997. 棉铃虫抗寒能力的研究. 生态学报, 17(3): 298–302.]
- Wu KM, Lu YH, Feng HQ, Jiang YY, Zhao JZ, 2008. Suppression of cotton bollworm in multiple crops in China in areas with Bt toxin-containing cotton. *Science*, 321(5896): 1676–1678.
- Wu QL, Zeng J, Wu KM, 2022. Research and application of crop pest monitoring and early warning technology in China. *Frontiers of Agricultural Science and Engineering*, 9(1): 19–36.
- Wu YD, Guan F, Shen HW, Yang YH, 2021. Research progress in the resistance status and molecular resistance mechanisms of the cotton bollworm *Helicoverpa armigera* to Bt protein Cry1Ac in China. *Journal of Plant Protection*, 48(5): 958–963. [吴益东, 管放, 沈慧雯, 杨亦桦, 2021. 我国棉铃虫对 Bt 蛋白 Cry1Ac 抗性现状及分子机制研究进展. 植物保护学报, 48(5): 958–963.]
- Wu YD, Shen JL, You ZP, 1995. Genetic analysis of fenvalerate resistance in cotton bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae). *Acta Entomologica Sinica*, 38(1): 20–24. [吴益东, 沈晋良, 尤子平, 1995. 棉铃虫对氰戊菊酯抗性遗传分析. 昆虫学报, 38(1): 20–24.]
- Xia B, Wang JQ, Zhang YJ, Feng XD, 2006. The establishment and application of crop pest monitoring and forecasting information system in China. *China Plant Protection*, 26(12): 5–7. [夏冰, 王建强, 张跃进, 冯晓东, 2006. 中国农作物有害生物监控信息系统的建立与应用. 中国植保导刊, 26(12): 5–7.]
- Xiao XZ, Xu JY, Zhang HY, Chu JX, Wu HH, 2023. Preliminary exploration of pest biological control mediated by the aggregation pheromone of *Arma chinensis*. *Journal of Tianjin Agricultural Science and Technology*, 2023(4): 10–14. [肖雪庄, 许静杨, 张华颖, 初吉兴, 吴惠惠, 2023. 蠋蛾聚集性诱剂介导的害虫生物防治初探. 天津农林科技, 2023(4): 10–14.]
- Xie JX, 2010. Characteristics of cotton bollworm occurrence and control techniques. *Beijing Agriculture*, 2010(22): 42. [谢敬雪, 2010. 棉铃虫的发生特点与防治技术. 北京农业, 2010(22): 42.]
- Xu JJ, Guo WC, Yao J, Tu EX, Wang ZP, Hamiti, Arkerdan, 2004. Study on using mass-release *Trichogramma chilonis* to control *Helicoverpa armigera* in cotton field in Xinjiang. *Xinjiang Agricultural Sciences*, 41(5): 378–380. [许建军, 郭文超, 姚举, 吐尔逊, 王泽鹏, 哈米提, 阿克旦, 2004. 新疆棉区利用赤眼蜂防治棉铃虫田间释放技术研究与应用. 新疆农业科学, 41(5): 378–380.]
- Xu Q, Jin MH, Xiao H, Peng Y, Zhang F, Li HR, Wu KM, Xiao YT, 2025. Genomic predictions of invasiveness and adaptability of the cotton bollworm in response to climate change. *Journal of Genetics and Genomics*, 52(9): 1109–1120.
- Xu YZ, He XY, Hou XQ, 2020. Demonstration and effectiveness of the green pest control technology for cotton bollworm using artificial egg propagation of *Trichogramma*. *Journal of Agricultural Engineering Technology*, 40(11): 18–19. [徐永芝, 何徐颖, 侯新强, 2020. 人工卵繁殖赤眼蜂绿色防控棉铃虫技术示范试验与成效. 农业工程技术, 40(11): 18–19.]
- Yan S, Li HT, Zhu WL, Zhu JL, Zhang QW, Liu XX, 2014. Effects of light intensity on the sexual behavior of the cotton bollworm, *Helicoverpa armigera* (Lepidoptera: Noctuidae). *Acta Entomologica Sinica*, 57(9): 1045–1050. [闫硕, 李慧婷, 朱威龙, 朱家林, 张青文, 刘小侠, 2014. 光强度对棉铃虫交配行为的影响. 昆虫学报, 57(9): 1045–1050.]
- Yang H, Yang EL, Zhang GY, Wan SQ, 2015. Advances in research and application of *Metarhizium* sp. against tobacco pests. *Chinese Tobacco Science*, 36(5): 101–107. [杨华, 杨恩兰, 张功营, 万树青, 2015. 绿僵菌防治烟田主要害虫的研究进展与展望. 中国烟草科学, 36(5): 101–107.]
- Yang SS, Lu MX, Tian LH, Bai SF, Yin XM, Li X, 2019. Exploring of morphological criteria for *Campoletis chlorideae* (Hymenoptera: Ichneumonidae) mass-rearing. *Henan Science*, 37(4): 564–569. [杨赛赛, 鲁梅雪, 田良恒, 白素芬, 尹新明, 李欣, 2019. 棉铃虫齿唇姬蜂人工繁育形态标准探讨. 河南科学, 37(4): 564–569.]
- Yang XM, Zhao SY, Liu B, Gao Y, Hu CX, Li WJ, Yang YZ, Li GP, Wang LL, Yang XQ, Yuan HB, Liu J, Liu DZ, Shen XJ, Wyckhuys KAG, Lu YH, Wu KM, 2023. Bt maize can provide non-chemical pest control and enhance food safety in China.

- Plant Biotechnology Journal*, 21(2): 391–404.
- Yang YH, Li YP, Wu YD, 2013. Current status of insecticide resistance in *Helicoverpa armigera* after 15 years of Bt cotton planting in China. *Journal of Economic Entomology*, 106(1): 375–381.
- Yu J, Zha M, Zheng MJ, Liu XX, 2020. Evaluation of the efficacy of *Beauveria bassiana* and *Metarhizium anisopliae* in controlling cotton bollworm under laboratory conditions. *Xinjiang Agricultural Sciences*, 57(4): 608–615. [于健, 查萌, 郑梦君, 刘小侠, 2020. 白僵菌和绿僵菌对棉铃虫的室内防控效果评价. 新疆农业科学, 57(4): 608–615.]
- Yu HL, Li YH, Li XJ, Romeis J, Wu KM, 2013. Expression of *Cry1Ac* in transgenic Bt soybean lines and their efficiency in controlling lepidopteran pests. *Pest Management Science*, 69(12): 1326–1333.
- Zalucki MP, Furlong MJ, 2005. Forecasting *Helicoverpa* populations in Australia: A comparison of regression based models and a bioclimatic based modelling approach. *Insect Science*, 12(1): 45–56.
- Zhang DD, Xiao YT, Chen WB, Lu YH, Wu KM, 2019. Field monitoring of *Helicoverpa armigera* (Lepidoptera: Noctuidae) *Cry1Ac* insecticidal protein resistance in China (2005–2017). *Pest Management Science*, 75(3): 753–759.
- Zhang F, Wang SQ, Luo C, Chen YH, Li F, 2004. Effects of the artificial diets and breeding means on growth and development of *Chrysopa septempunctata* Wesm. *Plant Protection*, 30(5): 36–40. [张帆, 王素琴, 罗晨, 陈艳华, 李凤, 2004. 几种人工饲料及繁殖技术对大草蛉生长发育的影响. 植物保护, 30(5): 36–40.]
- Zhang FY, Huang ZL, Gao LJ, Yu T, 2004. On occurring regulations and the preventing measures for cotton bollworms in Chao Yang area. *Journal of Liaoning Agricultural College*, 6(2): 15–16. [张福艳, 黄志礼, 高连军, 于涛, 2004. 辽宁朝阳棉区棉铃虫发生规律及防治对策. 辽宁农业职业技术学院学报, 6(2): 15–16.]
- Zhang HN, Yin WY, Zhao J, Jin L, Yang YH, Wu SW, Tabashnik BE, Wu YD, 2011. Early warning of cotton bollworm resistance associated with intensive planting of Bt cotton in China. *PLoS ONE*, 6(8): e22874.
- Zhang L, Lv SL, Li MJ, Gu M, Gao XW, 2022. A general signal pathway to regulate multiple detoxification genes drives the evolution of *Helicoverpa armigera* adaptation to xenobiotics. *International Journal of Molecular Sciences*, 23(24): 16126.
- Zhang L, Wu XW, 2003. Characteristics of cotton bollworm occurrence and control strategies in Hunan Province. *Hunan Agricultural Sciences*, 2003(6): 36–37. [张玲, 武向文, 2003. 湖南棉铃虫发生特点与防治对策. 湖南农业科学, 2003(6): 36–37.]
- Zhang XX, Liu Y, Guo MB, Sun DD, Zhang MJ, Chu X, Berg BG, Wang GR, 2024. A female-specific odorant receptor mediates oviposition deterrence in the moth *Helicoverpa armigera*. *Current Biology*, 34(1): 1–11. e14.
- Zhang YY, Bohan DA, Zhang CC, Cong WF, Munier-Jolain N, Bedoussac L, 2025. Crop diversity reduces pesticide use more efficiently with refined diversification strategies. *Communications Earth & Environment*, 6: 460.
- Zhang ZQ, Sun XL, Luo ZX, Gao Y, Chen ZM, 2013. The manipulation mechanism of “push-pull” habitat management strategy and advances in its application. *Acta Ecologica Sinica*, 33(2): 94–101.
- Zhou BL, 2004. Prediction of the fourth generation cotton bollworm population in the Jiangnan Plain cotton-growing region. *China Plant Protection*, 24(8): 31–32. [周柏龄, 2004. 江汉平原棉区第四代棉铃虫发生量的预测. 中国植保导刊, 24(8): 31–32.]
- Zhou Y, Wu QL, Zhang HW, Wu KM, 2021. Spread of invasive migratory pest *Spodoptera frugiperda* and management practices throughout China. *Journal of Integrative Agriculture*, 20(3): 637–645.
- Zhou Y, Wu QL, Zhao SY, Guo JL, Wyckhuys KAG, Wu KM, 2019a. Migratory *Helicoverpa armigera* (Lepidoptera: Noctuidae) exhibits marked seasonal variation in morphology and fitness. *Environmental Entomology*, 48(3): 755–763.
- Zhou Y, Zhao SY, Wang ML, Yu WH, Wyckhuys KAG, Wu KM, 2019b. Floral visitation can enhance fitness of *Helicoverpa armigera* (Lepidoptera: Noctuidae) long-distance migrants. *Journal of Economic Entomology*, 112(6): 2655–2662.