从害虫“综合治理”到“生态调控”

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摘要 害虫种群治理是农业昆虫学研究的核心问题,也是农业生态系统可持续性发展的重要基础。本文论述了害虫综合治理与生态调控的关系、地位、内涵和发展史,以及目前害虫种群治理的形势和需求。经典害虫综合治理(IPM)在集约化农业和粮食增产过程中发挥了重要作用,但这种体系框架下的害虫治理策略逐步引发了经济发展和生态环境之间的矛盾,尤其在全球变化加速的背景下,生态安全和环境健康问题日益凸显,这要求害虫种群治理更需要注重农业生态系统的可持续性,这就是害虫生态调控理论(EBPM)。EBPM能够在更全面的复合生态系统服务和生态文明建设层次上通过调控食物网拓扑学结构和能量流动,通过天敌的下行控制(top to down)和土壤的上行效应(bottom to up)共同调控害虫种群,最终实现害虫种群的可持续控制。因此,害虫综合治理到生态调控的转变和过渡是可持续农业的要求,也是在全球变化背景下维持农业生态安全的必然选择。

关键词 生态安全, 生态系统服务, 全球变化, 可持续性

害虫种群治理(pest population management, PPM)是农业昆虫学研究的核心问题,也是农业生态系统可持续性的基础^[1~3]。在过去几十年间,在“预防为主,综合防治”植保方针的指导下,害虫综合治理(integrated pest management, IPM)已经形成了全面完善的技术体系,包括物理、化学、生物、生态以及农业防治技术与方法^[4]。在我国农业现代化发展过程中,IPM体系广泛应用于控制多种重大农业害虫(麦长管蚜(*Sitobion avenae*)、麦二叉蚜(*Schizaphis graminum*)、棉蚜(*Aphis gossypii*)、棉铃虫(*Helicoverpa armigera*)及玉米螟(*Pyrausta nubilalis*)等),并发挥了重要作用,为农业生产力提高和集约化发展做出了巨大贡献^[5]。

虽然IPM已经得到了全面的应用,但在目前全球变化的背景下,随着农业生产力逐步提高,农业害虫危害还是呈现逐步猖獗的趋势,并且出现了爆发性

和规模性等特点,其中多种农业重大害虫连年暴发,给粮食生产带来了极大威胁和安全隐患^[6,7]。害虫危害剧增导致综合治理成本不断增加,形成了IPM策略与害虫种群不断协同进化发展的局面,造成我国农产品生产成本攀升。虽然IPM体系还在不断改进和完善,但在环境日益多变和害虫危害不断增加的条件下对生态系统可持续性和生态文明方面仍然显得非常不足^[8],这带来一个巨大挑战。在应对全球变化加速的过程中如何实现害虫种群可持续性控制,以保障农作物粮食安全生产和稳步提高。新植保方针“绿色植保,公共植保”的提出,给农业害虫种群治理提出了新要求,更加强调了绿色和生态安全的重要性^[9]。目前,害虫治理状况远不能达到新植保方针的要求,虽然国家大力倡导发展生物农药和绿色防控体系,生态安全和农业环境污染治理依然不尽如人意,使生产力提高与生态安全之间的矛盾日益加剧,

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迫切需要采用新理论和新方法来实现农业生产的可持续性和生态安全,这就是害虫生态调控(ecologically based pest management, EBPM)^[10]. 本文总结了经典IPM, 简述了IPM发展过程以及目前的局限性, 然后归纳了害虫生态调控, 并阐明了EBPM的特点和优势, 最终提出了IPM与EBPM的区别, 并认为将来害虫控制将会从IPM逐步转向EBPM^[11,12].

1 经典的害虫综合治理

IPM思想由来已久, 最初在1940年, Hoskins教授认为任何单一措施都不能很好地实现害虫控制, 只有多种方法综合起来才能够达到有效的害虫种群治理. 1965年, 联合国粮食及农业组织(Food and Agriculture Organization of the United Nations, FAO)与生物防治国际组织(International Organisation for Biological Control, IOBC)在罗马召开的“有害生物防治”会议上确定了害虫综合防治(integrated pest control, IPC)的专业术语, 从此掀起了害虫综合防治研究的国际大潮^[3]. 1972年, 在美国召开的环境质量保护会议(Council on Environmental Quality, CEQ)决定把IPC改为现在的IPM^[13], 同年FAO接受了IPM, 并认为与IPC具有相同的含义. 1975年, FAO才明确地定义了IPM(与IPC相同), 称为害虫管理系统, 在害虫种群动态与环境相互作用下, 利用所有相互兼容的技术和方法把害虫种群控制在引起经济损失水平以下^[14], 这种害虫综合治理概念影响深远, 沿用至今, 直到现在多数重大农业害虫防治策略都处于这一体系框架中^[15,16].

1979年, 我国生态学和昆虫学先驱马世骏先生^[17]对此作了更明确的定义: IPM是从生物与环境的整体观念出发, 本着预防为主的思想, 安全、有效、经济、简易的原则, 因地制宜, 合理运用农业的、化学的、生物的、物理的方法, 以及其他有效的生态手段, 把害虫控制在不到危害的水平, 以保证人畜健康和增加生产的目的. 马世骏的定义包括3个基本观点: 经济学、生态学与社会学观点, 然而, 在实际生产实践过程中, 这3个观点并不是并重的, 而是经济学观点一直主导着害虫综合治理方向, 主要是由于目前害虫综合治理技术体系是一种基于经济损失允许水平(economic injury level, EIL)理论框架, 经济损失允许水平是一个临界的害虫种群密度, 在这个密度时实施人工防治的成本刚好等于采取防治而得到

的经济利益, 这也是IPM的核心概念^[18].

经济损失允许水平非常强调经济成本和收益, 并且还借助了经济阈值(economic threshold, ET)的概念, 这也体现了经济学观点在IPM理论中的重要性^[19]. 对于IPM中生态学和社会学观点, 一直只是定性的描述, 到目前为止也没有量化的体系指标^[20]. 虽然IPM在概念上指出了害虫综合治理过程中应该考虑生态学和社会学观点, 但在实际生产过程中由于过度依赖经济损失允许水平和经济阈值的理论体系, 导致整个IPM体系完全受经济学观点驱动^[21], 而生态学和社会学观点并没有真正融入整个IPM系统, 也没有得到广泛运用, 只在具体操作方法和个别防治技术上有所体现. 例如, 在近年的IPM体系中逐步强调采用绿色防控技术(高效低毒农药与生物农药), 而高毒高污染的农药逐步被禁止和淘汰. 近年来大量害虫控制策略和新型农药制剂不断发展, 却一直没有离开经济损失允许水平和防治指标的理论范畴, 经济学基本观点一直主导着整个害虫综合治理过程^[4,22].

另外, IPM最大的特点是依靠外界物质和能量的投入, 来维持农业生态系统的高产出和稳定性. 虽然IPM体系为农业生产水平提高做出了卓越的贡献, 但形成了人类物质能量投入与害虫种群危害之间博弈对抗的局面, 双方不断改进博弈方式和强度, 形成了一种协同进化过程^[23,24], 此过程中, 虽然害虫种群危害强度和频率不断增加, 人类物质和能量的投入也不断增加, 最终给整个农业生态系统造成了极大的负担^[25]. 在这种对抗加剧的背景下, “虫害攻坚战”, 甚至“虫口夺粮”屡见不鲜, 甚至近年来这种情况更加恶化, 因此在保证粮食生产和生态安全的前提下, 如何缓和这种“人虫关系”可能是今后最大的课题^[26,27]. 目前IPM虽然能够很好地控制农业重大害虫, 但已经出现举步维艰, 少数出现进退两难的境地, 局部出现了大量的农药残留、土壤污染以及水资源污染, 给农业生态系统的可持续性带来了巨大压力, 迫切需要新型、全面、复合的害虫综合控制体系来保证生态安全和环境健康. Kogan^[3]也意识到了这些问题, 并对IPM重新做了总结和定义: IPM是一种害虫防治策略选择和使用的决策支持系统, 基于成本/收益分析, 采取单一或多种兼容的管理策略, 并且考虑对生产者、社会与环境的综合影响. 但这种定义仍然没有摆脱经济学核心的范畴, 生态与环境仍

然处于一种附属地位。

2 害虫生态调控

EBPM最早在1983年提出^[10,28],作为崭新的范式代替IPM体系,同时也是IPM的发展和继承,EBPM提出了4个重要的观点:(i)环境安全;(ii)高效、简便,并能结合其他生产方式;(iii)可持续性;(iv)以生态系统整体为中心^[29,30]。国内戈峰^[11]也独立提出了EBPM原理和方法,并清晰地给出了EBPM的思想框架,提出了EBPM的概念和内涵^[11]。EBPM是根据生态学、经济学和生态调控论的基本原理,充分发挥生态系统内一切可以利用的能量,综合使用包括害虫防治在内的各种生态调控手段,对生态系统及作物-害虫-天敌食物链的功能流进行合理的调节和控制,变对抗为利用,变控制为调节,化害为利,将害虫防治与其他增产技术融为一体,通过综合、优化、设计和实施,建立实体的生态工程技术,从整体上对害虫进行生态调控,以达到害虫管理的真正目的——农业生产的高效,低耗和可持续发展^[31,32]。EBPM强调功能高效、结构和谐、持续调控、经济合理4大基本原则,从思想和哲学高度上强调了生态系统的可持续性^[30,33]。庞雄飞院士对这种EBPM技术也做了深入研究和实践,并提出了大量的害虫种群调控手段和技术方法。近年来,不少国内学者逐步重视生态调控技术^[34]。张润志等人^[35]发明了苜蓿(*Medicago sativa*)-棉花(*Gossypium hirsutum* L.)的条带式种植,因为棉蚜与苜蓿蚜发生存在时间差,因此棉花-苜蓿条带式种植利用天敌在苜蓿和棉花上的空间转移很好地控制了棉蚜;尤民生^[2]深入探索了间套作模型对小菜蛾(*Plutella xylostella*)的控制作用,发现了不同作物间作和种植格局改变能够很好地控制害虫;赵紫华等人^[36,37]通过多年的田间实验发现农业景观格局是影响害虫种群动态及群落组成的重要因素,农业景观规划与设计是害虫种群治理的可行途径,主要是通过增加生境复杂性来为天敌提供栖息地和适宜的微环境。此外,转基因作物作为一种新型生态调控技术,在棉铃虫种群防治上得到全面的证明,抗虫棉(*Bacillus thuringiensis*, Bt)不仅有效地治理了靶标害虫棉铃虫,而且降低农药使用量,为天敌创造了生存空间和庇护所,给周围其他作物如玉米(*Zea mays*)等输出了大量的天敌资源,提高了生态系统服务^[38,39]。

EBPM思想认为农业生态系统中作物-害虫-天敌

系统与外部环境形成了一种内在耦合关系,相互作用,相互制约,通过物质、能量、信息和价值的流动构成一个有序的整体^[40]。而作物-害虫-天敌系统内部关系复杂,存在着多种物质交换和能量流动关系,甚至这个复杂的作物-害虫-天敌系统与土壤又形成了物质交换和能量流动,调控整个生态系统的结构组成和能量流动关系才能够从根本上解决害虫种群治理和农业生态系统可持续性的问题。EBPM以生态安全为核心,可持续性为基础,利用各种现代农业管理措施和生物技术方法改善农业生态系统本身的健康和抗性,包括地上作物健康与地下的土壤健康,强化生态系统和作物自身的免疫功能,调节农业生态系统中的食物网关系和能量流动方向,并以其他综合治理措施为辅助手段,来全面提高农业生态系统的可持续性,最终实现农业生态系统服务最大化。另外,EBPM最大的优势是能够从多尺度空间(田间、景观甚至区域)对害虫种群动态进行全面研究和控制,也更加有利于开展农作物病虫害的统防统治,全面降低和优化目前农户型防治带来的一系列环境问题^[41]。虽然目前EBPM策略还并没有得到广泛的应用和发展,但在一些小规模的有机农业中已经初见雏形,尤其在欧美等发达国家,一些有机果园和有机种植作物对害虫生态调控已经进行了深入研究,并且环境与经济得到了同步发展^[42,43]。

3 全球变化背景下害虫种群治理转变与生态系统可持续性

在全球变化背景下,包括气候变暖、生物入侵、氮沉降增加、土地覆盖变化及全球生物多样性丧失,给全球农业生态系统和生态安全带来了严峻的考验。面对这些足以导致生态系统崩溃的考验,研究生态系统可持续性和生态系统功能成为最大的挑战^[44]。对于农业生态系统,一方面要提高生产力水平,另一方面农业生态系统的可持续性和生态安全逐步上升成为重要的问题,尤其在一些生态脆弱区,如何恢复和维持生态系统功能的发挥成为亟待解决的问题。IPM只是在害虫种群治理和短期经济利益的框架内进行的,而在目前全球变化加速的背景下,必须以更全面和综合的生态系统观点进行害虫种群治理^[45]。

虽然IPM和EBPM目前在不少研究中还没有明确区分,但研究者认为由于思想、出发点、目标的不一致,IPM与EBPM既有相通之处,也有明显区别^[11]。

图1 综合治理到生态调控的范式转移

Figure 1 The paradigm shift from integrated pest management (IPM) to ecologically based pest management (EBPM)

因此“综合治理”是“生态调控”的基础和手段，“生态调控”是“综合治理”的继承和发展，两者有共同之处，但也存在完全不同的特点和优势(图1)^[41,46,47]。(i) 综合治理主要是基于经济因素的基础，兼顾社会效益和环境问题，关注短期的和局部的经济效益，而且经济阈值的理论基础导致综合治理一直未能有效地关注环境问题和社会效益；生态调控主要以生态系统功能与生态安全为前提，强调长期和整体的生态系统服务和生态系统可持续性^[48,49]。(ii) 综合治理侧重于人类活动采取的各类措施直接对害虫本身进行调控和管理(图1)；生态调控侧重于通过人类活动采取各类措施来加强作物和生态系统本身的健康程度，改变农业生态系统的食物网拓扑结构和能量流动关系，增强群落稳定性和作物抗性而间接对害虫进行调控^[42,50]。(iii) 生态调控以土壤-作物-害虫-天敌为整体，关注整个害虫控制的生态过程和机制，强调生态系统自身的健康和免疫能力，与新植保防治“公共植保，绿色植保”相得益彰(图1)。由于指导思想的不同，会导致具体操作措施和应对策略的不同，甚至会导致农业生产方式和管理过程彻底改变。在全球变化的背景下，在生态安全和环境健康日益受到威胁的挑战下，农业生产的高效低耗和稳定性将会受到更多的关注，EBPM作为一种全面考虑农业生态系统健康和可持续性的新理论和新方法，将会得到广阔的发展^[51,52]。

4 害虫生态调控理论与技术的重要研究方面

害虫生态调控作为新的范式，以生态系统功能

和服务为出发点，以生态系统可持续性为目标，通过多尺度时空下生境管理和现代生物工程技术为手段，恢复和提高作物及生态系统的健康程度。增强作物的免疫力和抗性，同时改善天敌种群在农业景观中的流动，最终通过结合上行效应(bottom to up)和下行效应(top to down)的策略来实现害虫生态调控^[12]。针对我国害虫生态调控模式，也提出了多尺度空间管理的策略，主要是以群落和生态系统为基础，以复合生态系统服务作为评价指标和手段，来全面地实现农业生态系统的可持续性。

农业生态系统突出特点是多作物组成和空间异质性，每种作物系统还存在特异性，即使同种作物上的不同种类害虫在营养、生理以及种间关系上也都存在种特异性^[53,54]。因此针对每种作物的害虫生态调控，还需因地制宜，具体分析群落组成和种间互作关系，才能有效地实现害虫生态调控^[55,56]。这需要一种新的生态系统功能和服务的评价体系，对每种策略进行模拟运算，在较长时间范围内对生态系统功能进行预测，最终选择优化方案^[41,57,58]。

虽然我国害虫生态调控技术在很多方面取得了巨大进展，如作物多样性种植、转基因棉、减免耕、间套作及轮作等，但整个EBPM系统仍然需要大量的技术补充和理论完善，至少5方面还需要进一步的研究^[59,60]：(i) 尺度效应：昆虫在不同的时空尺度下对环境变化的响应具有不对称性，并且昆虫的分布及种群动态与时空尺度密切相关，因此需要探索害虫种群动态及群落组成在不同时空尺度下的格局转换和演化过程，尤其是害虫及天敌种群的时空扩散及流动规律随时空尺度的变化规律^[25,47]。(ii) 群落食物网拓扑学及功能群：害虫-天敌的食物网拓扑学结构及功能解析能够揭示害虫暴发成灾机制，也能够阐明每个物种在生态系统中的功能和地位，并进一步探索群落功能群特征和多样性模式^[61,62]。(iii) 土壤-作物-害虫-天敌的耦合系统：害虫只是生态系统的一部分，结合地上作物系统与地下土壤系统的整合研究，来同时提高地上的作物健康和地下土壤健康，是将来农业生态系统可持续性研究的重要方面^[32,63]。(iv) 分子基因工程：分子基因工程技术大幅提高了作物进化速率和扩展了害虫生态调控手段，外源功能基因导入(转基因技术(transgene technology))与作物自身基因修饰(基因编辑技术(clustered regularly interspaced short palindromic repeats,

CRISPR/Cas9))已经形成2类成熟的技术手段。目前转基因作物的抗虫品种已经取得飞速发展和进步,在众多方面(抗虫、抗病、抗逆)已经形成了重要的商业产品,未来功能基因的探索发掘及研究还将是一个重要的领域^[23,64,65]。(v)大数据与宏生态学:生态系统由于其复杂性、多层次性及交叉性特征,尤其害

虫生态调控更加注重生态系统功能和可持续性^[66]。生态学数据已经呈现爆发性增长,不同的研究层次研究类型交叉复杂,而多类型、多层次的大数据整合分析还很缺乏,尤其是分子、个体、种群、群落、生态系统的综合的云分析将为宏生态学提供新的技术手段,为害虫生态调控提供更坚实的理论基础^[67]。

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From “Integrated Pest Management” to “Ecologically Based Pest Management”

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There have been substantial land cover changes in agroecosystems in the world during the last 50 years, including the intensified use of agrochemicals and expansion of croplands, resulting in rapid loss of biodiversity and reduction of ecosystem services. The effects of these changes, at both field and landscape scales, on biodiversity, species composition, pest population dynamics, community structure, interspecific and intraspecific relationships in agroecosystems have become increasingly important.

Pest population management is one of the most important issues in agricultural entomology and pest control, which is also the basis for agricultural sustainability. In the past decades, Integrated Pest Management (IPM) has developed into a comprehensive system aiming for controlling agricultural pests based on economic threshold (economic injury level) and control index of pest populations. Classic IPM has been playing a key role in intensified agriculture aiming for enhancing crop production. However, the high input and low efficiency of IPM in connection with the environmental problems such as pest resistance and water pollution have been highlighted by the whole society recently due to the intrinsic economics view. Although the environmental and social views were also emphasized by IPM in recent years. The whole IPM system was still based on economic thresholds while only particular technology was aimed to control agricultural pests with a green process. Additionally, IPM has simultaneously caused the dilemma between economic development and the agricultural environment (e.g. pesticide pollution). Therefore, there is an urgent demand for green methods to achieve pest population management and conservation of agricultural environments under the current situation, especially with the rapid development of global economy and international trades.

Ecologically Based Pest Management (EBPM) aiming for ecological safety and environmental health was first raised in 1983, which has been received substantial attentions worldwide. EBPM could improve the biological control on agricultural pests by recruiting natural enemies through mediating food web topology structure and energy flow within an arthropod community, which was also used to achieve multiple ecological services and ecological civilization in ecosystems. Additionally, EBPM could balance the interspecific relationship and community composition by improving the health of both plants and soil.

We review the theories, mechanisms, approaches and technology of EBPM, which could be applied on agricultural crops to achieve sustainable pest management. The pull-push strategy, associated resistance hypothesis, functional plant groups, and habitat management at multiple spatial scales were important mechanisms of EBPM. Technologies, like rotation, intercropping, no-tillage, cover crops, transgenic crops, and breeding, were important strategies, which have been successfully applied on some agricultural crops of China. Then, we also summarized the 5 important fields including scaling effects, community food web topology and functional groups, the coupling system of below- and above ground organisms, molecular and genetic engineering, and big data and micro-ecology. Finally, we concluded that the transition from IPM to EBPM could meet the requirements of agricultural sustainability and ecological safety, which was also an inevitable choice for enhancing ecosystem services and addressing environmental issues related to crop pest control under global changes.

ecological safety, ecological service, global change, sustainability

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