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综 述

气候变化对作物病虫害影响的研究进展

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摘 要: 全球气候变化通过加剧气温升高、改变降水格局和增加 CO₂ 浓度, 正在系统性地增加病虫害对农作物的危害, 对国家粮食安全构成严峻挑战。本文综述了我国农作物病虫害发生现状与特征、气候变化对病虫害发生态势的影响机制, 揭示了温度升高加速害虫发育与向北扩张、降水格局改变对病虫害的双向调控, 以及 CO₂ 浓度升高通过改变寄主植物生理间接影响病虫害动态的核心过程, 并强调多因子交互作用(如高温高湿)进一步放大了灾害风险。在应对策略上, 虽已初步形成涵盖抗逆育种与绿色农药开发、智能监测预警及适应性农艺措施的综合体系, 但现有研究在分子响应机制、动态过程量化及区域灾变模式整合上仍显不足。未来亟需突破“气候-作物-有害生物”系统的多维耦合机制, 融合多模态数据与人工智能, 构建主动适应的新型数据驱动防治体系。

关键词: 气候变化; 作物病虫害; 温度; 降水; 二氧化碳

Effects of climate change on crop diseases and insect pests

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Abstract: Global climate change is systematically exacerbating the damage caused by crop pests and diseases through increased temperatures, altered precipitation regimes, and elevated atmospheric CO₂ concentrations, posing severe challenges to national food security. This paper reviews the current status and characteristics of crop pest and disease occurrences in China, along with the mechanistic influences of climate change on their dynamics. It reveals the core processes, including accelerated pest development and northward expansion due to rising temperatures, bidirectional regulation of pests and diseases by altered precipitation patterns, and the indirect impact of elevated CO₂ concentrations on pest and disease dynamics by changing the physiology of host plants. Furthermore, interactions among multiple factors (such as combined heat and humidity) are shown to amplify risks substantially. While a preliminary integrated framework has been established—encompassing stress-resistant crop breeding, development of green pesticides, smart monitoring and early warning systems, and adaptive agronomic practices—significant knowledge gaps remain. These include insufficient understanding of molecular response mechanisms, limited quantification of dynamic processes, and fragmented modeling of regional disaster patterns. Moving forward, it is imperative to advance research on the multi-dimensional coupling mechanisms within the “climate-crop-pest” system, integrate multi-modal data and artificial intelligence technologies, and develop a proactive, data-driven prevention and control system for enhanced resilience.

Keywords: climate change; crop pests and diseases; temperature; precipitation; carbon dioxide

自工业革命以来, 由于人类活动和自然因素的共同影响, 世界正经历着以全球变暖为显著特征的

气候变化^[1-2], 尤其近些年的全球气温更是不断打破历史纪录^[3]。目前, 气候变化愈加严峻, 出现了高温

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日数增加、连续干旱时间延长、季节性降雨延迟、融雪洪水提前、暴雨洪涝加剧等不利形势^[4-5],造成作物产量减少、品质下降、土壤退化以及农业水资源危机等不利局面^[6-9],严重影响了农业生产与粮食安全^[10-11]。此外,气候变化愈加严重的情况为病虫害小范围发生到大区域暴发和流行带来了极为有利的条件,其为害程度呈逐渐加重趋势^[12]。据联合国粮农组织估计,每年粮食产量因病虫害发生遭受的损失占总产量的 24%,其中随着气候变化引起的虫害每年造成全球作物生产损失达 10%~16%,并且在农业和林业地区正在大幅增加^[13]。

作物病虫害的发生,会受到多种非生物因素(如光、温度、水等)动态变化的影响^[14]。有研究表明,温度升高、降水变化、极端天气频发等都会影响病虫害的繁殖、生存、传播,以及其与环境、天敌之间的关系^[15-17],不同程度增加病虫害流行暴发风险。预计 2025 年我国主要粮食、油料、蔬菜等作物的 23 种重大病虫害将呈加重态势,全国预计发生面积 16,786.5 万公顷,其中气象因子就是导致该现象的重要因素之一^[18]。此外,巴西^[19]、印度^[20]、撒哈拉以南的非洲^[21]等地均因作物病虫害多发重发造成主要作物产量减少,损失较大。

气候变化背景下,重大病虫害突然暴发、快速流行、严重危害的特点愈加明显,这使得病虫害防控、保障国家粮食生产及质量安全面临新的挑战^[22]。因此,揭示农作物病虫害在气候变化下的发生和变化规律,不断创新病虫害防治策略,最大限度地降低有害影响,对农业生产效率有效提升和农作物种植业稳步发展极为重要。本文从我国作物病虫害发生现状,温度、降水、CO₂变化、多气候因子交互作用对病虫害的影响,以及对应的病虫害防控策略等方面展开综述,为后期研究提供科学依据,为农业生产实践中的病虫害防治提供指导。

1 我国农作物病虫害发生现状

1.1 总体发生态势与危害程度

在我国,农作物病虫害是最主要的生物灾害,自 1970 年以来,我国作物的虫害和病害的发生率大幅增加,1970—2016 年期间,全国作物病虫害的平均发病率已增加了 4 倍(从 53%增加到 218%)^[23]。华北平原和长江中下游平原的主要生产地区作物受灾最重,病虫害群体主要为鳞翅目(37%)、同翅目(22%)和真菌(28%)^[24]。2024 年我国三大粮食作物

水稻、小麦、玉米病虫害共发生超 1.6 亿公顷,因其危害实际损失率 3.1%^[25]。据统计,小麦、水稻病虫害常年发生面积分别约 7000 万公顷和 8000 万公顷,造成产量损失分别为 25~30 亿千克^[26]、33 亿千克^[27],并且玉米主要病虫害带来的产量损失总量自 2010 年已持续超过了水稻^[28]。此外,棉花、马铃薯、油菜、大豆等重要作物病虫害也呈现加重趋势^[29-32],预计 2025 年其发生面积为 833.3 万公顷,较 2024 年增加 5.8%^[33]。

1.2 主要农作物病虫害种类与区域特征

据统计,我国农作物病虫害近 1600 种,其中虫害 800 多种,病害 700 多种;能造成重大损失的有 100 多种,有重大流行性、迁飞性病虫害 20 多种^[34]。据 2023 年《一类农作物病虫害名录》公布,我国目前一类重大病虫害包括草地贪夜蛾、飞蝗、草地螟等 10 种虫害和小麦条锈病、小麦赤霉病、稻瘟病等 8 种病害^[35],这些都严重影响了农作物的健康生长以及产量和质量提升,为农业发展和粮食安全带来极大威胁^[36]。

农作物病虫害的发生与成灾,是作物品种、耕作栽培制度、有害生物、气象条件、管理措施等综合作用的结果^[37-40],其中气象条件是导致病虫害发生流行的关键因素之一,会直接或间接影响病虫害与环境及其他物种之间的关系,导致病虫害的发育繁殖、迁移分布和适应的改变^[41-45]。不同病虫害有着各自发育繁殖的适宜温度、湿度、光照等气象因子及气候背景(表 1)。例如,降水多、空气湿度大有利于喜湿性病害,如小麦条锈病、小麦赤霉病等的发生发展,但对蚜虫、棉铃虫等虫害的扩展蔓延会产生一定的抑制作用^[46]。

2 气候变化对作物病虫害的影响

气候变化对作物病虫害的影响是一个复杂的过程,涉及气候因子、寄主植物以及病虫害自身三者之间多层次的相互作用。虽然早期的研究多聚焦于温度等单一因素的影响,但这种方法难以完全揭示病虫害在真实农业生态系统中的复杂响应规律。现代研究普遍认为,气候变化是通过其关键驱动因子,即温度升高、降水格局改变和 CO₂ 浓度攀升协同作用于作物系统。这些气候驱动因子不仅能直接影响病原体和害虫的生理代谢、繁殖速率和地理分布,还会通过改变寄主作物的生长状况、营养品质及防御体系,对其产生深远的间接影响。为系统性地

表 1 我国一类农作物病虫害主要发生区及易发生气象条件

Table 1 Major occurrence areas and favorable meteorological conditions for class I crop diseases and insect pests in China

病虫害 Insect pest and plant disease	取食口器类型 Pest feeding mouthparts type	病害类型 Disease type	常用防控药剂 Commonly used defense	主要发生区 Main occurrence area	易发生气象条件 Prone to meteorological conditions
小麦蚜虫 Aphid	刺吸式 Piercing-sucking	—	吡虫啉、啉虫脒、氯氟·噻虫胺等 ^[47] Imidacloprid, acetamiprid, chlorofluorothiamethoxam, etc. ^[47]	黄淮海麦区, 北方麦区 ^[48] Huang-Huai-Hai wheat area, northern wheat area ^[48]	繁殖最佳温度 16–22℃ ^[49-50] Optimal breeding temperature 16–22℃ ^[49-50]
小麦条锈病 Yellow rust	—	真菌 Fungus	戊唑醇、氟环唑、丙环唑、己唑醇等 ^[47] Tebuconazole, epoxiconazole, propiconazole, hexaconazole, etc. ^[47]	西北、西南、华北及江汉流域 ^[51] Northwest, Southwest, North China and Jiangnan River Basin ^[51]	生长最佳温度 10–15℃, 降水充足 ^[52] Optimum growth temperature 10–15℃, adequate precipitation ^[52]
小麦赤霉病 Fusarium head blight	—	真菌 Fungus	多菌灵、氰烯菌酯、戊唑醇、丙硫菌唑等 ^[47] Carbendazim, phenamacril, tebuconazole, prothioconazole, etc. ^[47]	长江中下游及黄淮冬麦区 ^[53] The middle and lower reaches of the Yangtze River and the Huang-Huai winter wheat area ^[53]	相对湿度大 ^[54] High relative Humidity ^[54]
稻飞虱 Rice planthopper	刺吸式 Piercing-sucking	—	金龟子绿僵菌、三氟苯嘧啶、烯啶虫胺、球孢白僵菌等 ^[55] <i>Metarhizium anisopliae</i> , triflumezopyrim, nitenpyram, <i>Beauveria bassiana</i> , etc. ^[55]	淮河以南稻区 ^[56] Rice area south of Huaihe River ^[56]	生长最佳温度 20–30℃, 湿度高 ^[57] Optimum growth temperature 20–30℃, high humidity ^[57]
稻纵卷叶螟 <i>Cnaphalocrocis medinalis</i> Guenee	咀嚼式 Chewing type	—	苏云金杆菌、短稳杆菌、乙基多杀菌素、多杀霉素等 ^[55] <i>Bacillus thuringiensis</i> , <i>Bacillus brevis</i> , spinetoram, spinosad, etc. ^[55]	淮河以南的水稻主产区, 以华南、江岭和江淮稻区为主 ^[58] The main rice producing areas in the south of the Huaihe River are mainly in South China, Jiangling and Jianghuai rice areas ^[58]	相对湿度 75%以上 ^[58] Relative humidity above 75% ^[58]
二化螟 <i>Chilo suppressalis</i>	咀嚼式 Chewing type	—	苏云金杆菌、金龟子绿僵菌等 ^[55] <i>Bacillus thuringiensis</i> , <i>Metarhizium anisopliae</i> , etc. ^[55]	华中稻区 ^[59] Central China rice region ^[59]	温度 23–26℃、湿度 85%–100% ^[60] Temperature 23–26℃, humidity 85%–100% ^[60]
稻瘟病 Rice blast	—	真菌 Fungus	枯草芽孢杆菌、春雷霉素、三环唑、丙硫唑等 ^[55] <i>Bacillus subtilis</i> , kasugamycin, tricyclazole, propylthiozole, etc. ^[55]	东北, 南方丘陵山区, 沿江沿淮稻区 ^[18] The main rice producing areas in Northeast China, hilly and mountainous areas in South China, along the Yangtze and Huai River regions ^[18]	适宜温度 24–28℃, 湿度较高 ^[61] Suitable temperature 24–28℃, high Humidity ^[61]
南方水稻黑条矮缩病 Southern rice black-streaked dwarf virus	—	病毒 Virus	三氟苯嘧啶、噻虫嗪、呋虫胺等 ^[55] Triflumezopyrim, thiamethoxam, dinotefuran, etc. ^[55]	海南岛, 两广地区, 云贵地区 ^[62] Hainan island, Guangdong and Guangxi region, Yunnan and Guizhou region ^[62]	冬春温暖, 降水偏多 ^[63] Warm winter and spring, more precipitation ^[63]

(续表 1)

病虫害 Insect pest and plant disease	取食口器类型 Pest feeding mouthparts type	病害类型 Disease type	常用防控药剂 Commonly used defense	主要发生区 Main occurrence area	易发生气象条件 Prone to meteorological conditions
亚洲玉米螟 Asiatic corn borer	咀嚼式 Chewing type	—	苏云金杆菌、球孢白僵菌、氯虫苯甲酰胺等 ^[64] <i>Bacillus thuringiensis</i> , <i>Beauveria bassiana</i> , chlorantraniliprole, etc. ^[64]	我国从南至北的玉米产区 ^[65] China's corn producing areas from south to north ^[65]	温度 17–22℃, 相对湿度 60% ^[66] Temperature 17–22℃, relative humidity 60% ^[66]
玉米南方锈病 Southern corn rust	—	真菌 Fungus	枯草芽孢杆菌、井冈霉素 A、苯醚甲环唑等 ^[64] <i>Bacillus subtilis</i> , validamycin A, difenoconazole, etc. ^[64]	黄淮海夏玉米区 ^[67] Huang-Huai-Hai summer corn region ^[67]	日平均气温 25℃左右, 降水较多 ^[67] Average daily temperature about 25℃, more precipitation ^[67]
马铃薯晚疫病 Potato late blight	—	真菌 Fungus	代森锰锌、烯酰吗啉、氟噻唑吡乙酮等 ^[68] Mancozeb, dimethomorph, oxathiapiprolin, etc. ^[68]	西南及中原产区 ^[69] Southwest and central plains producing areas ^[69]	适宜温度 20℃左右, 湿度大 ^[70] Suitable temperature about 20℃, high humidity ^[70]
油菜菌核病 Sclerotinia rot	—	真菌 Fungus	氟唑菌酰胺、腐霉利、啶酰菌胺等 ^[71] Pydiflumetofen, procymidone, boscalid, etc. ^[71]	以长江流域油菜主产区为主 ^[72] The main producing areas of rapeseed in the Yangtze River Basin are the main producing areas of rapeseed ^[72]	相对湿度 85%以上, 偏酸性环境 ^[73] Relative humidity of more than 85%, acidic environment ^[73]
大豆根腐病 Root rot	—	真菌 Fungus	氟环唑、啮菌酯、精甲霜灵等 ^[74] Epoxiconazole, azoxystrobin, etalaxyl-M, etc. ^[74]	黄淮海和南方等大豆产区 ^[75] Soybean producing areas such as Huang-Huai-Hai and South China ^[75]	降水多 ^[76] More precipitation ^[76]
飞蝗 <i>Locusta migratoria</i> L.	咀嚼式 Chewing type	—	高效氯氟菊酯、马拉硫磷、金龟子绿僵菌等 ^[77] Beta-cypermethrin, malathion, <i>Metarhizium anisopliae</i> , etc. ^[77]	东亚飞蝗, 华北和江淮等平原地区; 亚洲飞蝗, 西北, 东北地区; 西藏飞蝗, 川藏河谷地区 ^[78] East Asian migratory locust, plain areas such as North China and Jianghuai plains; Asian migratory locust, Northwest and Northeast China; <i>Locusta migratoria tibetensis</i> , Sichuan-Xizang River valley areas ^[78]	高温干旱 ^[79] High temperature and drought ^[79]
粘虫 Army worm	咀嚼式 Chewing type	—	苏云金杆菌、辛硫磷、氯吡硫磷等 ^[80] <i>Bacillus thuringiensis</i> , phoxim, chlorpyrifos, etc. ^[80]	除新疆外均可暴发成灾 ^[81] Disasters can break out except in Xinjiang ^[81]	气温较高, 温室气体增加 ^[82] Higher temperatures and increased greenhouse gases ^[82]
草地贪夜蛾 Fall angle army-worm	咀嚼式 Chewing type	—	苏云金杆菌、球孢白僵菌、氯虫苯甲酰胺等 ^[83] <i>Bacillus thuringiensis</i> , <i>Beauveria bassiana</i> , chlorantraniliprole, etc. ^[83]	华南, 长江以南, 江淮黄淮地区 ^[84] South China, south of the Yangtze River, Jianghuai and Huanghuai regions ^[84]	温暖湿润 ^[85] Warm and humid ^[85]

(续表 1)

病虫害 Insect pest and plant disease	取食口器类型 Pest feeding mouthparts type	病害类型 Disease type	常用防控药剂 Commonly used defense	主要发生区 Main occurrence area	易发生气象条件 Prone to meteorological conditions
草地螟 Meadow moth	咀嚼式 Chewing type	—	甲维•三唑磷、三唑磷等 ^[86] Emamectin triazophos, triaazophos, etc. ^[86]	华北、东北和西北地区 ^[87] North, Northeast and Northwest China ^[87]	温度 22℃左右, 相 对湿度 60%–80% ^[88] Temperature about 22℃, relative hu- midity 60%–80% ^[88]
蔬菜蓟马 Vegetables thrips	锉吸式 File suction type	—	施球孢白僵菌、乙基多杀菌 素、多杀霉素等 ^[89] <i>Beauveria bassiana</i> , spine- toram, spinosad, etc. ^[89]	长江流域, 华南地区蔬菜田 ^[90] Vegetable fields in the Yangtze River Basin and South China ^[90]	温度 20–30℃, 相对 湿度 40%–70% ^[91] Temperature 20– 30℃, relative humi- dity 40%–70% ^[91]

解析这些复杂的互作关系, 本章将从以下 2 个方面展开详细论述: 首先, 分别探讨温度、降水和 CO₂ 浓度这 3 个核心气候变量变化对作物病虫害带来的独立影响; 其次, 分析这些因子之间的交互作用如何放大或改变病虫害的动态与危害程度^[92], 其总体互作关系如图 1 所示。

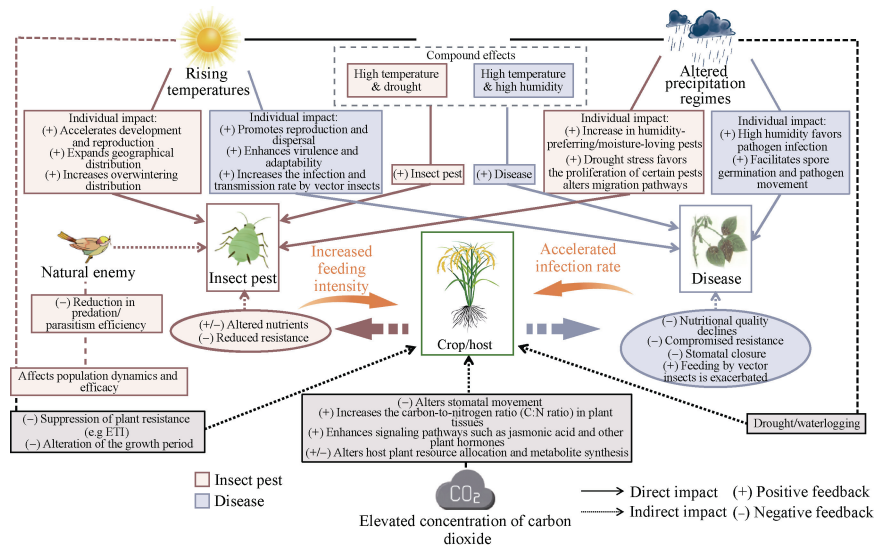


图 1 气候变化-病虫害-作物互作图
Fig. 1 Climate change-pest and disease-crop interaction diagram

2.1 温度变化的影响

全球气候变暖正深刻改变着农业害虫的发生为害情况, 主要表现为发育周期缩短、世代数增加、分布范围扩张以及取食活动增强等。对于大多数虫害而言, 温度升高会加速其新陈代谢和发育繁殖, 每升高 10℃其代谢率往往会增加一倍^[93-94]。当温度升高时, 害虫体内的酶促反应(如呼吸作用、蛋白质合成等)和相关基因表达会明显加快, 提高细胞分裂速度和营养转化, 从而加快害虫的生长发育^[95-96]。目前, 粘虫已普遍在原有基础上增加 1~2 代^[97], 亚洲玉米螟^[98-99]、棉铃虫^[100-101]等害虫数量也已激增,

为害程度加重。但是, 害虫适应性进化的分子基础尚不明确, 高温促进的相关基因表达途径也存在争议, 这也将是未来深入研究的重点。此外, 温度升高还会影响温带滞育害虫的越冬存活率以及大部分害虫的扩散。尤其是暖冬天气, 显著降低了其越冬死亡率, 使原本受低温限制的害虫能够扩散到以前因冬季低温而被排除在外的新地区^[102-104]。自 1960 年以来, 虫害就以平均每年(2.7±0.8) km 的总体速度向极地扩散, 且北半球较南半球更快^[105-107], 利用生态模型预测也发现, 目前高纬度虫害负担明显增加^[91], 橘小实蝇^[108]、木瓜秀粉蚧壳虫^[109]等都因温度升高

在地理分布上有了明显的变化,并且预计稻飞虱在中国中东部和澳大利亚中南部的中纬度地区也将有新的越冬区^[110],但虫害向两极具体迁移过程中的种群变化、新地区适应性等动态过程还未明确量化。温度升高还会增强害虫取食活动以及改变物候同步性,这些会严重影响作物生育期和生理生化,使其抗性降低,导致植食性害虫的取食增加^[103,111],中国农业科学院植物保护研究所粮食作物害虫监测与控制创新团队发现,温度升高会降低小麦的水杨酸(SA)和茉莉酸(JA)抗性途径的相关基因表达和酶活性,从而导致小麦抗性降低,加重小麦蚜虫取食^[112]。

对于大部分病害而言,温度升高也是加剧其侵染危害的核心驱动力,它直接促进病原体存活、繁殖、毒力进化等,并抑制作物关键抗病机制,导致病害严重度上升。温度升高会促进部分病原体存活与繁殖,减少其越冬死亡率,且生长季温度适度升高也会加速病原菌的生长、孢子产生和传播^[113-114]。例如,温度升高可加快小麦条锈病菌的发育速度,增加孢子产量^[115],加重油菜菌核病、小麦赤霉病等病害的严重程度^[73,116-117],西班牙巴勃罗·德·奥拉维德大学 Manuel Delgado-Baquerizo 团队预测发现,气候变暖下全球潜在植物病原体的相对丰度将总体增加^[118]。温度升高还使得许多病原体毒力与适应性增强,病原菌可能在较高温度下产生更多毒素或进化出更强的适应性。例如,稻瘟病菌、大豆锈菌、大豆疫霉菌等都已出现新的菌种^[119],小麦病害的病原菌种群也发生了适应性变化,条锈病的致病菌已从偏好凉爽潮湿条件的温和菌种转向更具侵略性偏好温暖潮湿条件的菌种^[120],且 2 种攻击性较强的高温适应菌株也已传播到三大洲^[121],这将进一步导致病害加重。此外,温度升高还会抑制植物效应子触发免疫(effector-triggered immunity, ETI)相关基因表达,通过影响作物的宿主植物抗病性而加剧病害发生^[122-123]。与虫害研究相似,温度对病害的影响在分子机制研究、过程量化等方面都存在不足,高温促使部分病原菌毒力增强还缺少大量试验证据,温度驱动机制也存在争议,并且作物-害虫-病原互作的温度阈值还是未知数,部分研究还忽略了温度对于天敌和微生物的影响。

目前环境温度已普遍上升到许多病虫害生长发育的最佳温度^[124],根据气候模型和生物参数分析发现,当全球平均地表温度上升 2℃时,由于病虫害压力,小麦、水稻和玉米的产量损失中位数增长分

别为 46%、19%和 31%,且在温带地区受到的影响最大^[125]。然而,温度升高对病虫害的影响存在显著的区域异质性。例如,对 80 种真菌及霉菌植物病原体的评估预测,至 21 世纪末,病原体物种丰富度将在低纬度地区下降,而在高纬度地区(特别是欧洲和中国)则趋于增加;相比之下,巴西、撒哈拉以南非洲、印度和东南亚地区则呈现下降趋势^[91],害虫的地理分布也观测到类似的纬度迁移模式^[126]。此外,过去 30 年夏季气温的持续上升,已导致感染旋果蚊子草的锈病原等局部灭绝^[127],并且当锈病大豆处于 37℃下暴露后,会减轻病害症状^[128]。模型预测也进一步指出,全球变暖到 2050 年可能导致约 15%~37%的昆虫物种面临灭绝风险^[129]。这些发现都为理解气候变化背景下病虫害的演化动态提供了新的视角,目前温度变化可能会阻止或进一步加剧未来的潜在流行病,但不同的病原体毒性的分布和变异性差异较大,这为相关研究带来了新的挑战^[130]。未来还应多深化分子层面的响应机制,强化区域性、极端高温等的相关研究,不断进行试验和监测分析,为后续防治提供科学基础。

2.2 降水模式改变的影响

在全球变暖背景下,降水在时空上的不均一性也显著驱动着虫害的发生与扩散,其直接影响害虫生存环境、繁殖速率、物理致死效应以及关键迁飞行为等,导致多数虫害危害加重,地理分布格局发生改变。降水变化可能会改善害虫的生存环境,有利于部分害虫卵的孵化和幼虫存活,土壤上部线虫、小麦蚜虫、粘虫、稻飞虱等都会在雨日快速增长^[131-135]。而部分害虫则因最适湿度较低,在高温干旱时繁殖加快、种群数量增长,对象主要有蚜虫、红蜘蛛、甜菜夜蛾、番茄红螨、螟虫等^[136-140]。并且干旱部分害虫会增强将植物作为水源的进食能力,增加对农作物的损害。此外,暴雨可能会冲走虫卵和幼虫,造成物理影响而减少种群数量,其中蚜虫、螨虫、白蝇等体型较小的害虫更易被大雨影响^[141]。并且降水还会影响迁飞性害虫的路径与生态适应性,粘虫^[82,142]、稻纵卷叶螟^[143-144]、蚜虫^[128]等的迁飞速度和降落地点都受到降水影响,其会因降水、下沉气流、低温等天气过程而迫降,形成区域性聚集降落,且在降水增加时会明显减弱迁飞速度和距离^[145-146]。南京农业大学胡高教授团队指出,受降雨南移影响,一些褐飞虱将在到达长江下游主要水稻种植区之前降落,加重了降落地的虫害^[147]。虽然目前研究已得

出降水变化对虫害影响的发生规律,但害虫如何响应干旱、迁飞路径和降落地如何精准预测以及极端降水事件对天敌-害虫的行为机制的影响等的研究都存在局限,后续还需不断完善。

对于病害而言,降水模式的变化对其有双向作用,主要表现为高湿促进部分病原体侵染与毒性,加剧高湿型病害;干旱则可能削弱作物抗性并增强特定病原体毒力,导致部分旱生型病害加重。孢子发芽和感染宿主植物都需要一定湿度,且降水增多时会促进孢子发芽和细菌运动性,从而加重病菌毒性^[115,148]。核盘菌^[149]、辣椒疫霉^[150]、大豆疫病菌、马铃薯晚疫病菌^[151-152]等的毒性都随着空气湿度的增加而增加,且当空气相对湿度超过 80%时,核盘菌感染生菜的发病率最高。此外,干旱胁迫诱导也会引起病害变化,主要通过降低作物生理抗性 or 加强病害毒性等造成^[153-154]。在干旱压力下,作物的碳水化合物、蛋白质、激素水平等生理代谢活动都会受到影响^[155-156],因抗病性减弱而感染。但每个病理系统都会有一个“临界缺水”,即植物水分应力和病原体攻击性(受水分影响)之间的平衡相交^[157],所以病害在不同湿度条件下的影响具有差异性。水稻稻瘟病原体和链霉菌^[158]、某些马铃薯细菌性结痂病原体^[159]在较低水分条件下会增加病原体数量和毒性严重程度;而在新西兰,豌豆根腐病、洋葱白腐病、小麦冠腐病等病害都随着干旱长度和频率的增加而加重^[160],猕猴桃、葡萄^[161]等的某些病害则明显减轻;且在过去 30 年,干旱还使得澳大利亚牧场北方炭疽病(*Kabatiella caulivora*)流行边界向西收缩近 200 km^[162]。但仅仅得出发生规律并不能为后续预测和防治提供较好的科学基础,目前在病原体湿度感知与毒力激活的机制研究、湿度对于不同病害的阈值分析以及降水-土壤湿度对病害的综合影响等方面的研究都存在不足,缺少深度机理和实例验证。

2.3 CO₂ 浓度升高的影响

截至 2022 年 10 月,全球 CO₂ 水平已增加到 418 μmol mol⁻¹,预计 21 世纪末将达到 570 μmol mol⁻¹^[163],其与作物病虫害发生有着明显的依赖性反应。CO₂ 浓度的增加通过改变植物营养与防御物质,对病虫害产生促进或抑制的双重效应,显著调控其种群动态与行为。对虫害来说,CO₂ 浓度上升会增加寄主植物组织中的碳氮比(碳含量增加,氮含量下降)导致生物合成发生变化,进而影响植物营养物质和二级防御物质的含量和成分,间接导致害虫的

进食行为、生长发育^[164-166]。部分害虫呈现显著的正向响应,CO₂ 浓度升高时棉蚜会延长 30%的韧皮部汁液摄取时间^[167];西花蓟马因寄主叶片可溶性糖含量升高诱发糖脂代谢紊乱,摄食量增加 40%^[168];褐飞虱则表现为卵期与若虫发育历期缩短 5.96%~11.59%,同时单雌产卵量提升 12.24%,卵孵化率增加 4.14%^[169];中国农业科学院植物保护研究所抗虫功能基因研究与利用创新团队发现,棉铃虫将植物释放的 CO₂ 作为产卵信号,优先选择 CO₂ 浓度较高的幼嫩叶片产卵^[170]。此外,还有部分抑制效应或双重效应,例如,稻纵卷叶螟在 CO₂ 水平升高的情况下,幼虫体重下降 15%、存活率降低 20%,蛹期缩短 12%伴随孵化率削减 18%^[171];象鼻虫种群密度也降低 25%,并伴随着个体生物量减少^[172];部分蚜虫则因代谢成本增加触发应急响应,寿命缩短 12%^[173]。贵州大学曹宇团队发现,高浓度 CO₂ 会显著加快所有蓟马物种的发育速度,但却降低了其存活率,且不同蓟马种类在繁殖力、内禀增长和净生殖 3 个方面存在显著差异^[174]。CO₂ 浓度升高会通过影响作物而间接导致虫害增加或减少已有较多的实例验证,并且已总结部分害虫的响应规律和为害情况,但具体的 CO₂-作物-虫害机制还未得到系统研究,作物中激素、基因、细胞等的影响路径和虫害如何感知作物变化而加重取食等还具有较大的研究空间。

对于病害而言,其影响主要表现为 4 种路径:首先,CO₂ 富集通过重编程植物免疫系统,增强茉莉酸、乙烯、植物激素等信号通路基础表达,改变作物抗性^[175-177];其次,CO₂ 升高还会改变植物气孔的运动,导致气孔密度和孔径的减少^[178-179];并且其还会改变寄主植物营养分配与代谢物合成,进而影响病害对作物的侵染程度与范围^[180-181];此外,还存在协同互作网络的改变,例如,小麦对 *Z. tritici* 和 *F. graminearum* 的防御效能因 CO₂ 升高而下降^[182],且会重塑小麦-大麦黄矮病毒-蚜虫媒介的互作网络^[183]影响病害发生。CO₂ 浓度升高还会促使锈病^[184-185]、瓜类白粉病^[186-187]、小麦赤霉病和小麦壳针孢叶枯病^[182]等病害明显增加。值得注意的是,不同病害对 CO₂ 浓度升高反应有着易感性差异。例如,爱荷华州立大学团队发现,大豆在高 CO₂ 浓度条件下对细菌病原体的抗性增强,而对某些病毒和真菌病原体等的易感性明显增加,对卵菌病原体的感染则无显著影响^[188],这也为后续研究和防治策略提出了新思路,同一作物在面对 CO₂ 浓度升高时其感染的细菌、真

菌、病毒、卵菌等可能会呈现出不同的多重效应,具有差异性机制。目前,与温度和降水相比,CO₂浓度升高对作物病害影响的研究还处于初级阶段,主要探究其通过影响作物间接导致病虫害发生变化,而直接影响的研究还较少,且 CO₂ 调控的植物免疫网络、相关基因表达路径、抗性改变机制均存在不足,部分研究只考虑了其中一条途径,没有进行综合性、系统性分析。后续,在突破分子机制解析、开展直接影响、构建多因子互作途径等方面还需不断突破。

2.4 多因子交互作用

作物病虫害发生时常伴随多个气候因子的共同影响,因此研究不同因子的交互作用也十分重要^[189]。目前已有部分研究揭示温湿度、风速、CO₂等气候要素的交互作用对病虫害动态的影响,其中温湿度效应研究最多,主要聚焦于高温高湿对病害和高温低湿对虫害的影响。高温高湿环境下,多种病原体位于其“黄金区间”,主要表现为孢子萌发率提高,侵染速度加快^[100-101]。例如,常见的麦瘟病^[190-191]、小麦条锈病、稻瘟病^[61]、柑橘黑斑病^[192]等的流行强度在高温高湿下明显加重,在南半球,预计到 21 世纪中叶,小麦产量每年因气候变化产生的麦瘟病将减产 6900 万吨^[193]。与病害不同,多数虫害都在高温低湿的环境下更易暴发。一方面高温会加速害虫的发育速率和繁殖代数,另一方面干旱胁迫导致植物的营养物质发生变化,为害虫提供更优食物源^[41-42]。蚜虫、红蜘蛛、甜菜夜蛾、番茄红螨、螟虫等^[136,140]的流行强度在高温低湿下明显加重。另外,受到温度、湿度等的综合影响,害虫的适生环境发生变化,如黄斑蕉弄蝶、红棕象甲和椰子木蛾在中国适生区的显著位移^[194],大豆害虫在温度-降水的协同作用下致使北美东南部、南美、东亚等地区风险加剧等^[195]。此外,气候-病原体-媒介昆虫-作物的跨界交互作用研究也取得了初步进展,例如,高温会加大南方水稻黑条矮缩病毒的媒介蚜虫的感染和传播速率^[196],CO₂ 浓度升高会诱导植物水杨酸等信号通路,改变媒介昆虫的取食行为,进一步提高植物病毒的传播效率^[197]。并且病原体还可能使得媒介昆虫对环境压力的适应性更强,应对气候变化,加重作物感染和损失^[198-199]。目前多因子交互作用虽已取得一定成果,但仍存在不足。多气象因子如何在分子、细胞等水平影响病虫害生长与迁移以及病害-媒介昆虫的反应机制等尚不明确;部分研究集中在试验或短期分析,关于多因子交互作用下病虫害的长期动态变化

趋势尚存在不确定性;此外,多因子交互考虑到作物生态环境、天敌等的研究较少,无法进行较全面的模拟预测和防治分析。

3 气候变化下作物病虫害防治策略

目前,我国以保障国家农林生产安全、农产品质量和农林生态安全为根本目标,坚持病虫害防控“防风险、堵漏洞、强基础、补短板”的工作原则,针对各项瓶颈问题不断强化创新,致力于大幅提升我国重大病虫害防控技术水平^[200-201]。针对气候变化和极端天气下的防治策略主要包括以下 3 个方面:第一,改良抗逆品种和研发化控制剂,以应对全球变暖背景下病虫害加剧的态势;第二,完善智能监测与预警系统;第三,构建适应气候变化特征的病虫害防控技术体系。

3.1 改良抗逆品种和加强化控制剂

我国为应对气候变化加剧的病虫害威胁,目前已围绕基因调控、微生物环境优化以及开发新型农药等多层次策略,全方位增强作物的自身抗逆性并减少病虫害损失。在抗逆品种方面,核心思路在于挖掘和聚合优良基因资源。例如,南京农业大学吴益东教授团队提出“基因聚合”策略将不同杀虫机制的 Bt 蛋白结合使用,显著延缓害虫抗性的产生^[202];华南植物园鲁显楷团队提出,利用 CRISPR 基因编辑、RNA 干扰及宏基因组引导工程等核酸技术手段,实现对根际功能的精准调控^[203],为作物可持续改良开辟新路径使作物能够更好地应对异常气候等胁迫因子,减轻病虫害损失;还利用化学物质改善土壤中有益微生物的数量和特征,提高抗病虫害能力等^[204-205]。这些都为解决作物抗病性提供了有效途径,赋能作物主动应对愈加严峻病虫害态势的韧性。

此外,在病虫害直接防控中,化学防治还是主要的手段,但过度使用农药化学品会导致生物多样性降低^[206],对生态系统、人类健康都存在潜在风险,因此开发环境友好型绿色防控产品极为重要。目前全球已利用天然产生的物质来控制农作物病虫害,以减少对农田生态系统造成的不利影响^[207-208]。贵州大学杨松课题组通过经典的 Pictet-Spengler 反应,合成了 31 个结构新颖的 1,2,3,4-四氢-β-咔啉(THC)衍生物,致力于以 THC 为活性骨架创制新型杀菌剂^[209];同时,通过跨物种 RNA 干扰(RNA interference, RNAi)也已研发出核酸农药投入使用^[210-211]。此

外, 南京农业大学农林生物安全国家重点实验室发现, FgPMA1 在禾谷镰刀菌中可以作为新型药剂靶标^[212], 继续开发核酸农药。这些都为更具针对性和高效性的绿色农药开发提供了重要科学依据, 但未来可能仍需继续攻克技术转化瓶颈, 提高新型农药效率、微生物田间稳定性等, 提升农业系统应对气候变化下病虫害加剧的韧性。

3.2 智能监测与预警系统

我国在农作物病虫害监测预警技术上已取得显著突破, 正步入智能化、精准化的新阶段。目前, 我国在利用光谱遥感、昆虫雷达、图像识别等技术对农作物病虫害进行监测预警方面取得重要进展^[213], 为病虫害的早期发现和预警提供了强有力的工具支撑。并且我国正在针对不同地区的不同病虫害进行预报模型的建立, 例如, 建立北方冬小麦主产区 8 个省(市)的小麦蚜虫发生面积划分等级和气象适宜度预报模型^[214]、湖北省小麦条锈病与气象因子的模型^[215]、安徽省小麦赤霉病综合气象条件指数和风险指数^[216]等。与此同时, 技术层面的融合与数据发展也在不断深化。逐步完善了多尺度、多类型病虫害特征的信息数据的构建, 注重高精度传感器研发及多遥感数据相融合, 提高了病虫害监测精度, 为后续研究提供数据支持^[36]。然而, 面对气候变化加剧导致的病虫害频发、重发态势, 现有的监测预警体系仍需不断进化升级。用从分子到全球范围的病虫害生物学和生态学等跨学科方法来预测, 将现有病原体生物学数据与运输、贸易、气候和地理深度耦合, 提高发病率的监测和预测能力。建立生化传感器、病霉监测站、人工智能平台等, 助力气候变化下病虫害预测和防治^[217]。此外, 尤需重视的是, 气候变化本身具有显著的区域异质性^[15], 并伴随着气象因子不同的速度、模式的变化, 因此未来研究可能需要重点关注“针对性”和“动态响应能力”的预测预警体系。

3.3 适应气候变化特征的病虫害防控技术体系

目前, 我国在构建基于农业措施调控的病虫害防治体系方面已打下坚实基础。通过综合运用调控农田小气候(如建设防护林、优化灌溉)、改革种植制度(合理轮作、间作、套作)、合理灌溉等一系列农艺措施, 缓冲气候压力, 增强土壤传播病害的防治能力^[218-221]; 并且通过调节播期来规避不利的气候条件, 发展多样化种植模式, 不断提高农业生态系统的韧性。但由于目前气候变化下病虫害发展的严峻

形势以及作物生理的复杂性, 还需以生态理论为框架, 综合作物自身生理代谢机制、生物相互作用、土壤条件等来应对, 要将现有的入侵理论、微生物群落共存理论、植物与环境互作理论等形成一个强大的框架^[222], 构建气候变化-作物-病虫害的防治体系, 根据气候变化进行保护型生物防治、气候智慧型害虫管理技术、精准农业等^[37]。值得一提的是, 基于气候变化特征的病虫害防控技术体系从“被动应对”到“主动适应和调控”的跃升, 可能是未来重要发展方向, 为保障粮食安全筑起更坚固的生态屏障。

4 总结与展望

农作物病虫害已步入高频率、高危害的阶段, 研究表明气候变化已极大影响了农作物以及病虫害, 且与气候变化相关的许多未知因素仍然存在。气候变化通过温度升高、降水格局改变、CO₂ 浓度升高等多维度驱动因子, 系统性地影响着农作物病虫害的发生动态与侵染取食机制^[130]。温度升高显著加速了大多数害虫发育周期与繁殖代数, 增强了部分病原菌毒力与适应性, 且扩张了病虫害地理分布^[92]; 降水格局改变的调控主要呈现双向效应, 高湿环境促进孢子萌发与害虫发育运动, 而干旱胁迫则削弱作物抗性并激活旱生型病原体; CO₂ 富集则重点影响植物-病虫害互作, 一方面改变寄主组织营养物质诱导害虫补偿性取食, 另一方面则影响植物免疫信号与气孔行为, 加剧了病虫害流行^[223]; 此外, 多因子交互作用也进一步放大了灾害风险, 高温高湿下多数病害侵染加速, 高温干旱下大部分虫害取食加重等。目前, 面对气候变化驱动的病虫害加剧态势的防治也不断完善, 逐渐构建抗逆品种改良和化控制剂、智能监测与预警系统、农业措施防治的三重防治体系, 逐步推动多学科、多检测、多源传感器与 AI 融合精准监测与风险预判, 为应对非稳态气候下病虫害的复杂演化提供了系统性解决方案。

但是, 气候变化和病虫害都具有复杂性和不确定因素, 且相互之间并不是单一因素的影响, 目前的影响机制和模型建立多以单因子或温度、降水双因子展开, 农艺措施防治和生物化学防治都没有针对性地研究和推广, 还处在不断创新、试验阶段, 且研究的区域覆盖性不强, 多尺度、多类型长期动态监测不足。所以, 未来应重点开展以下方面的研究: 结合气候变化、作物、种植管理等多因素综合性分析, 针对病虫害发生态势与机理展开区域性研究,

完善气候变化-作物-有害生物系统的多维度耦合机制; 深入研究影响作物的生物分子机制, 并结合大数据平台、AI 等建立病虫害影响情况和分区建模框架; 注重多模态数据深度耦合, 提高气象卫星、病虫害检测及捕捉传感器、作物生物生理研究, 深度探索“气候-作物-病虫害”的机理特征; 融合深度学习与机理模型, 动态输出作物抗性品种布局、生物农药施用阈值等, 构建新型数据防治体系, 为构建气候适应性病虫害防控体系提供科学支撑。

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