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作物病虫害遥感监测研究进展与展望

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摘 要：病虫害是农业生产过程中影响粮食产量和质量的重要生物灾害。目前，我国的作物病虫害监测方式以点状的地面调查为主，无法大面积、快速获取作物病虫害发生状况和空间分布信息，难以满足作物病虫害的大尺度科学监测和防控的需求。近年来，随着国内外卫星光谱、时间和空间分辨率的不断提升，利用遥感手段开展高效、无损的病虫害监测成为有效提升我国病虫害测报水平的重要手段。与此同时，多平台、多种方式的作物病虫害遥感监测也为病虫害的有效防治和管理提供了重要科技支撑。本文从作物病虫害光谱特征、遥感监测方法和遥感监测系统等方面阐述了作物病虫害遥感监测研究的进展，分析了当前面临的挑战，并对未来发展趋势进行了展望。

关键词：作物；遥感；病虫害监测；未来展望

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1 引言

作物病虫害是农业生产过程中影响粮食产量和质量的重要生物灾害[1,2]。在全球范围内，与病害相关的粮食产量损失约占全球粮食总产量的14%，与虫害相关的粮食产量损失约占全球粮食总产量的10%[3]。据全国农业技术推广服务中心2018年公布的数据，中国每年因病虫害的发生和危害导致的直接粮食损失约占总产量的30%。2010年"中央一号文件"提出要支持开展农作物病虫害专业化统防统治，加强重大病虫害监测预警能力建设[4]。对病虫害进行早期预警和防控对减少农业化学药剂的使用量和残留量，促进生态环境和国家食品安全，以及对于中国粮食贸易策略制定和社会经济发展均具有重要战略意义。

随着遥感科技和计算机技术的发展，利用遥感手段对作物病虫害进行"非接触式"的监测逐渐被应用于农业生产过程中。而随着近年来遥感数据尺度的极大丰富，对病虫害遥感监测模型方法的研究已成为农业遥感领域中一个重要研究内容[5-9]。随着遥感与其他数据类型之间联系的不

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断加强，各个层面的研究均得到了深化，遥感技术在农作物病虫害监测、病虫害预测预报以及田间精准防控和管理等方面都有着不同程度的应用。

利用遥感技术不仅能够对作物病虫害的发生范围进行监测，也能够对不同病虫害胁迫的发生类别和严重程度进行识别和区分[2,10-12]。各类机载、星载的精密测控传感器的发展为不同的用户需求提供了多重“时—空—谱”分辨率的遥感信息，这为准确、快速地了解作物病虫害发展状况提供了宝贵契机。而随着遥感技术及病虫害监测水平的不断提高，一些新的信号处理技术、机器学习方法和模式识别算法在监测建模中被不断应用[6,13-17]。本文介绍了当前国内外作物病虫害遥感监测方法和技术，阐述了作物病虫害遥感监测在监测方法、监测系统研发与应用等方面的研究进展，并在此基础上分析了作物病虫害遥感监测目前所面临的挑战，同时也展望了未来发展的趋势。

2 作物病虫害遥感监测方法研究进展

随着遥感卫星数据源的不断丰富，近几年新发射的中国高分（GF）系列、欧洲航天局的哨兵系列（Sentinel series）等，加之已有的中国的风云（FY）系列、环境（HJ）系列，美国的Landsat系列卫星等，使得遥感观测数据的空间分辨率和时间分辨率都得到了极大提升[18]。近年来，利用遥感手段进行作物病虫害监测，主要针对不同的遥感数据源的特点，对不同病虫害胁迫下的光谱响应特征进行分析，通过选取病虫害敏感性波段所表现的波普特性，对遥感信号进行分析和建模，从而实现病虫害的监测和分类。

2.1 基于高光谱分析技术的遥感监测

基于高光谱技术的作物病虫害监测研究主要集中在可见光波段和近红外波段。通过高光谱观测获取的作物连续的波谱信息在病虫害遥感监测和识别方面的主要有以下两方面的应用：一方面利用高光谱传感器可以同时获取作物病虫害胁迫的光谱差异和纹理差异，进而结合两方面的差异性信息提取胁迫特征；另一方面，获取的高光谱波段信息可以有效表征由病虫害引起的叶片理化组分的变化差异。

作物受病虫害胁迫后引起的叶片表面“可见—近红外”波段的光谱反射率的变化是病虫害遥感的直接特征，反映了植被物理生化组分的响应。病虫害引起的光谱响应研究已引起了很多学者重视，并被广泛应用于遥感监测和早期胁迫诊断研究[19-22]。Luo等[23]研究了生长了蚜虫的小麦叶片的光谱响应，结果表明，在700~750nm、750~930nm、950~1030nm和1040~1130nm处叶片的光谱反射对小麦蚜虫的响应率显著；除此之外，利用原始光谱的特征变换形式可以有效地加强波谱特征的差异，从而提取出目标病害的类别和严重程度。例如，Spilenlli等[24]对梨树冠层光谱数据进行了求导，通过筛选对梨树火瘟病较为敏感的导数特征进行了火瘟病的遥感识别和早期监测，并对不同维度光谱信息的对比分析，发现高维的光谱信息包含更多与病害胁迫相关的特征，能够对病害胁迫进行较为精确的早期监测。Purcell等[25]利用高光谱分析仪测定了不同侵染等级下的甘蔗样本，并通过傅里叶变换（Fourier Transform，FT）对光谱的纹理信息进行了提取，接着利用主成分分析法筛选了重要的特征变量，并用偏最小二乘法（Partial Least-Square Method，PLS）对筛选特征与不同病害严重度进行了建模分析，结果表明二阶微分光谱相比于其他特征拥有更高的监测精度，在病害早期识别中有较大的应用潜力。

另一方面，对敏感波段进行组合构成的光谱指数不仅拥有明确的物理意义，还能突显病虫害的生理生化过程，从而从生物学机制的角度实现对病虫害的监测和区分。Shi等[26]通过接种实验获取了小麦条锈病、白粉病和蚜虫的冠层高光谱数据，通过相关性分析筛选了敏感波段并基于敏感波段提取了多个植被指数特征，之后通过多种

核判别分析构建了多种非线性分类器，并利用所构建的分类器对冠层进行了监测识别，结果表明，基于Sigmoid核函数构建的非线性分类器能够获得较高精度的监测效果。Naidu等[21]通过野外实验获取了受葡萄卷叶病侵染的葡萄叶片高光谱数据，通过相关性分析发现绿波段和近红外波段的光谱反射率对病害胁迫有显著的响应。随后，基于敏感波段构建了相关的植被指数，实现了对葡萄卷叶病的高精度遥感识别。在这些研究的基础上，越来越多的学者发现作物病虫害在不同的光谱波段中表现出不同的响应[27-29]，因此如何针对不同的病虫害种类，在实际监测中需要寻找和构建具有高专一性的监测指标，选择较为合适的模型构建方法是作物病虫害遥感监测中继续解决的关键问题[30-32]。目前较为普遍的思路是通过寻找与病虫害严重度较为敏感的高光谱波段来提取和构建相关的光谱特征，表1为当前主要的作物病虫害遥感识别和监测的光谱特征，用于区分和识别不同病虫害胁迫。

表1　用于病虫害高光谱特征区分的一阶微分、连续统特征及植被指数

Table 1 The first derivative features，continuum features and vegetation indices used in discrimination of pest and disease

类别	指标	名称	定义	文献
微分光谱	Db	蓝波段一阶微分最大值（蓝边）	蓝边一般分布在490~539nm波段范围	[33]
	λb	Db的波长	λb表征了蓝边 Db处的波长	[33]
	SDb	蓝波段一阶微分光谱的和	表征了蓝边部分35个波段一阶微分光谱的和	[33]
	Dy	黄波段一阶微分最大值（黄边）	黄边一般分布在550~582nm波段范围	[33]
	λy	Dy的波长	λy表征了黄边Dy处的波长	[33]
	SDy	黄波段一阶微分光谱的和	表征了黄边部分35个波段一阶微分光谱的和	[33]
	Dr	红波段一阶微分最大值（红边）	红边一般分布在670~737nm波段范围．	[33]
	λr	Dr的波长	λr表征了红边Dr处的波长	[33]
	SDr	红波段一阶微分光谱的和	表征了红边部分35个波段一阶微分光谱的和	[33]
连续统特征	DEP550-750	光谱深度	波段范围550~750nm	[24]
	DEP920-1120		波段范围920~1120nm	[34]
	DEP1070-1320		波段范围1070~1320nm	[34]
	WID550-750	半波段宽度DEP	波段范围550~750nm	[34]
	WID920-1120		波段范围920~1120nm	[34]
	WID1070-1320		波段范围1070~1320nm	[34]
	AREA550-750	DEP和WID组成区域的面积	波段范围550~750nm	[34]
	AREA920-1120		波段范围920~1120nm	[34]
	AREA1070-1320		波段范围1070~1320nm	[34]
植被指数	GI	绿度指数（Greenness Index）	R_{554}/R_{677}	[35]
	NDVI	归一化植被指数（Normalized Difference Vegetation Index）	$(R_{NIR}-R_{R})/(R_{NIR}+R_{R})$	[36]
	TVI	三角植被指数（Triangular Vegetation Index）	$0.5*[120*(R_{750}-R_{550})-200*(R_{670}-R_{550})]$	[37]
	PRI	光化学反射指数（Photochemical Reflectance Index）	$(R_{570}-R_{531})/(R_{570}+R_{531})$	[38]
	CARI	叶绿素吸收率指数（Chlorophyll Absorption Ratio Index）	$(\|(a670+R_{670}+b)\|/(a2+1)1/2)*(R_{700}/R_{670})$ $a=(R_{700}-R_{550})/150, b=R_{550}-(a*550)$	[39]

续表

类别	指标	名称	定义	文献
	MCARI	修正的叶绿素吸收率指数(Modified Chlorophyll Absorption Reflectance Index)	$[(R_{700}-R_{670})-0.2*(R_{700}-R_{550})]*R_{700}/R_{670}$	[21]
	$CI_{Red-edge}$	红边叶绿素指数(Red-edge Chlorophyll Index)	$(R_{NIR}/R_{E})-1$	[40]
	SIPI	结构无关色素指数(Structural Independent Pigment Index)	$(R_{800}-R_{445})/(R_{800}+R_{680})$	[41]
	PSRI	植物衰老反射指数(Plant Senescence Reflectance Index)	$(R_{678}-R_{550})/R_{750}$	[41]
	NPCI	归一化叶绿素比值指数(Normalized Pigment Chlorophyll Ratio Index)	$(R_{680}-R_{430})/(R_{680}+R_{430})$	[41]
	OSAVI	优化的土壤调节植被指数(Optimized Soil Adjusted Vegetation Index)	$(R_{NIR}-R_{R})/(R_{NIR}+R_{R}+0.16)$	[42]
	SR	简单比值指数(Simple Ratio Index)	R_{1600}/R_{819}	[43]
	WI	水份指数(Water Index)	R_{900}/R_{970}	[21]
	NDWI	归一化插值水份指数(Normalized Difference Water Index)	$(R_{860}-R_{1240})/(R_{860}+R_{1240})$	[19]
	AI	蚜虫指数(Aphid Index)	$(R_{740}-R_{887})/(R_{691}-R_{698})$	[44]
	GNDVI	绿波段归一化植被指数(Green Normalized Difference Vegetation Index)	$(R_{NIR}-R_{G})/(R_{NIR}+R_{G})$	[20]
	DSSI2	损伤敏感光谱指数2(Damage Sensitive Spectral Index 2)	$(R_{747}-R_{901}-R_{537}-R_{572})/(R_{747}-R_{901}+R_{537}-R_{572})$	[44]
	HI	健康指数(Healthy Index)	$(R_{534}-R_{698})/(R_{534}+R_{698})-0.5R_{704}$	[12]
	RTVI	定量三角植被指数(Ration Triangular Vegetation Index)	$[55(R_{750}-R_{570})-90(R_{680}-R_{570})]/[90(R_{750}+R_{570})]$	[45]

注：R表示反射率（Reflectance）

2.2 基于航空/航天平台的多光谱遥感监测

在区域尺度上，随着航空/航天遥感平台的不断完善，国内外构建起了完善的遥感对地观测体系，为病虫害的大尺度遥感监测提供了技术支撑。Held等[46]通过分析受甘蔗锈病胁迫的甘蔗光谱数据，利用DWSI指数对EO-1 Hyperion高光谱影像进行了分析，成功实现了研究区病虫害发生范围的监测。Yuan等[45]通过星地联合实验获取了陕西关中地区小麦白粉病的地面高光谱数据，并利用SPOT-6卫星影像，基于SAM算法将地面高光谱数据与多光谱影像进行了融合，对小麦白粉病进行监测，结果表明监测精度达78%，说明基于SAM算法的地面高光谱与多光谱影像融合技术能够应用于病虫害遥感监测。Lenthe等[47]通过接种实验获取了小麦条锈病和白粉病的地面测量数据，同时也获取了对应的热红外影像，通过选取敏感特征并构建监测模型，全局精度达到了88.6%。Yang等[48]对棉花根腐病上的多光谱和高光谱图像信息进行了比较，结果认为多光谱影像在大区域的病虫害遥感监测和识别方面能达到较为满意的效果。Pan等[33]对甜菜叶斑病的研究表明，400~900nm光谱范围内的反射率特征能够对叶斑病实现精确监测。Zhang等[17]分别利用马氏距离法（Mahalanobis Distance，MD），偏最小二乘回归（Partial Least Squares Regression，PLSR），最大似然法（Maximum Likelihood Estimate，MLE）和混合调谐滤波的混合像元分解法（Mixture Tuned Matched Filtering，MTMF）对小麦白粉病进行监测，在区域尺度上，采用多时相遥感卫星影像对病害的发生和发展进行监测，结果表明，耦合PLSR和MTMF的监测方法对区域尺度的白粉病监测精度达到78%。

相较于大尺度的卫星遥感观测，基于航空遥感平台的机载高光谱/多光谱传感器除用到目标作物的光谱特征外，也需要对图像的结构和纹理特征进行解析。例如，Kim等[38]对获取的机载

遥感影像的信息熵、对比度等纹理特征基于颜色共生矩阵方法进行了提取，从而实现了柚皮病进行检测和病害识别，分类精度达到96.7%。Panmanas等[49]对大豆黄斑病、疮痂病、黑点病的高光谱遥感影像进行分析，结合光谱信息和纹理信息实现了病虫害的区分和识别。此外，值得注意的是，在多病害分类和识别方面，有学者尝试利

用计算机图形学的算法对病虫害的表征信息进行识别。Wang等[50]利用无人机影像种显示的番茄瘟病、纹枯病和胡麻斑病的病斑纹理结构特征，对三种病害进行了区分和监测。Yao等[51]基于作物在遥感影像中的方向一致性特征，对多种小麦病虫害进行了识别。

农田地块尺度和区域尺度下基于航空/航天平台的多光谱病虫害遥感监测特点及应用案例见表2。

表2 基于航空/航天平台的多光谱病虫害遥感监测特点及应用案例

Table 2 Remote sensing monitoring characteristics and application cases of multispectral diseases and pests based on aerospace platform

观测尺度	常用设备	载荷平台	特点及应用	病虫害类型	参考文献
农田地块尺度监测	成像多光谱仪，热红外成像仪	多旋翼无人机，固定翼无人机，传统大飞机	观测范围较大，成本较高，精度较高，以航空飞行器为平台，输出田间病害处方图。	小麦条锈病	[52-55]
				小麦白粉病	[56,57]
				小麦蚜虫	[58,59]
				小麦黄斑病	[60]
				葡萄黄化病	[61]
				水稻稻飞虱	[62]
				水稻稻瘟病	[63]
				芹菜菌核病	[64]
				番茄潜叶蛾	[65]
				番茄细菌性叶斑病	[66]
				甜菜褐斑病	[67]
区域尺度监测	多光谱卫星（Landsat，GF，Sentinel），高光谱卫星（Hyperion），热红外卫星（Landsat，Aster，HJ）	卫星遥感平台	观测范围极大，成本低，以遥感卫星为数据源，作为大尺度检测和预报提供依据。	小麦条锈病	[68,69]
				小麦白粉病	[70]
				小麦蚜虫	[69]
				水稻稻飞虱	[71]
				水稻矮缩病	[72]
				棉花根腐病	[73]

总体而言，基于高光谱遥感影像对区域尺度上的病虫害监测研究过多的依赖于遥感手段获取的地物光谱信息，较少的考虑了田间小气候、病虫害生境、人为因素等多元数据的影响，因此，对于融合遥感与其他多元数据对病虫害进行监测的研究尚不完善，且系统性较弱，未来在基于多元信息融合研究基础上的病虫害监测方面的工作有待加强。

3 作物病虫害监测系统研究进展

目前，作物病虫害监测系统一般由知识库、数据库、算法层、分析层和展示层等5部分组成，通常以数据库和算法层等为核心。目前国际上已经开发了多种病虫害监测系统，并被广泛地应用于田间病虫害胁迫诊断及管理等方面。例如，美国伊利诺伊大学牵头研制的农情系统Comax/Gos-sym通过其自研的监测和诊断系统确定了灌溉、施肥、施药和施用脱叶剂的最佳方案，推动了棉田管理和病虫害防治的信息化和自动化[74]；美国康奈尔大学和联合国粮食及农业组织联合开发了全球谷物锈病监测系统BGRI，应用该系统对全球的锈病进行监测并指导防治，在保证作物产量的前提下，可以节约30%左右的锈病杀菌剂使用量[75]；国际玉米小麦育种和改良中心（Centro Internacional de Mejoramientode Maizy Trigo，CIMMYT）开发了小麦玉米病害监测系统，该系统可以为作物病虫害的早期识别提供及时的预警，为农民的田间防控提供指导意见；美国拜耳公司研究出了一种农情实时监测系统Climate，农户可以通过该系统选择和搭建针对性的专家决策系统，使用者能够基于自身的情况创建知识库和模型库，这种模式赋予了系统很高的实用性和灵活性，能够快速便捷地进行二次及多次开发。

但是，上述系统的主要缺点是数据源过于单一，即数据来源主要是传统的气象观测站、地面调查网络、以及用户上传的田间数据，没有充分利用遥感等多源异构信息在农情系统决策中的作用。系统产出的大尺度病虫害监测产品只能为病虫害发展的中期和长期趋势进行评价，无法有效地应对实时的病虫害防控和管理需求。中国科学院研发的作物病虫害遥感监测与预测系统耦合了高分辨率遥感影像以及气象、植保等多源空间数据集，对中国主要粮食产区的小麦、水稻、玉米病虫害进行连续地监测和制图，可为当地植保部门的病虫害防治决策提供科学的数据支撑。总体而言，随着遥感对地观测手段的多样化，作物病虫害监测系统还不够完善，如何将作物病虫害遥感监测算法集成到业务化运行的大尺度遥感监测系统中，是未来作物病虫害遥感系统构建要解决的关键问题。

4 作物病虫害遥感监测未来展望

4.1 复杂环境条件下的病虫害遥感监测

现阶段的作物病虫害遥感监测方法在实际农业管理应用中，对田间环境、作物种植模式等条件有较高的依赖性，导致病害遥感监测的精度、稳定性和通用性方面与实际生产需求有一定的差距。目前，对病虫害的遥感监测研究正逐渐从单一时相反射率特征的提取向多时相探测病虫害引起的连续波谱变化方向转变。并在此基础上，考虑到田间土壤类型、气候类型等环境条件的影响，逐步开展病虫害病理机制的遥感监测，从而满足复杂田间环境下的农作物监测要求。另一方面，利用遥感信息与植物病理机制相结合的方法对病虫害生境变迁的范围和程度进行监测是实现病虫害早期预警的关键环节。因此，应依据不同类型病虫害的特异性建立综合作物病虫害光谱特征和生境特征所表达的病虫害不同方面的响应，从根本上控制农药用量。

4.2 病虫害动态持续监测

现阶段对作物病虫害的遥感监测大多针对某一个或几个病虫特征较为明显的生育期，对作物病虫害的整体发生发展的过程监测研究较少。尽管在病虫特征较为明显的生育期进行遥感监测研究能够获得较高的监测精度，但是监测时间较晚，不利于病虫害的防治和及时控制。病虫害的发生与发展是一个连续的过程，作物受侵染部位的生物物理变化是跟踪不同阶段寄主与病虫原相互作用关系的重要指标。目前，随着多种遥感平台的出现及日益普及，多尺度的连续时间病虫害动态监测越来越成为可能。在冠层尺度上，如何基于高光谱观测数据获取病虫害发生发展过程中的关键监测指标并构建精确的监测模型；在田块尺度上，如何基于无人机近地面飞行数据，结合病虫害高光谱特征进行精确的严重度估测和范围监测；在区域尺度上，如何基于病虫害光谱特征，结合多时相遥感卫星数据，综合考虑气象、

生境、菌源等因子，构建综合的病虫害监测方法体系，是未来研究的重要研究方向。

4.3 全球尺度病虫害遥感监测系统

目前，随着遥感对地观测手段的多样化，对病虫害遥感监测系统提出了更高要求。系统需要同时满足遥感监测的实时性、监测结果的准确性以及监测产品推广的便捷性。协同应用多源遥感观测数据构建全球尺度的病虫害遥感监测系统，实现病虫害的精准监测是病虫害遥感监测系统未来的趋势。

近年来，随着中国对地观测计划的顺利实施，一系列高光谱分辨率、高空间分辨率和高时间分辨率卫星成功发射，这些卫星协同作用，为建立多尺度作物病虫害遥感监测和预测系统提供了数据支持，使得作物病虫害遥感监测系统的研发成为未来农业精准管理的重要研究方向。

5 总结

近年来，随着遥感技术的不断发展，以及研究者对遥感数据在农业管理和监测方面应用的不断深入，使得遥感技术进行作物病虫害监测逐渐成为可能。本文分别从作物病虫害的光谱特征、监测方法以及系统研发等几个方面对现阶段作物病虫害遥感监测方法进行了总结和展望。虽然目前的遥感监测技术与实际生产管理的需求仍然存在一定的差距，但在实际应用中，通过将现有病虫害监测模型与田间环境条件与菌源状态等因子相结合，并充分考虑病虫害病理学知识的基础上，深入挖掘遥感技术在病虫害监测方面的潜力，可为中国农业大面积精准管理和植保提供精确、实时、大范围的监测信息。

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Progress and prospects of crop diseases and pests monitoring by remote sensing

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Abstract: Global change and natural disturbances have already caused a severe co-epidemic of crop pests and diseases, such as aphids, fusarium, rust, and powdery mildew. These threats may result in serious deterioration of grain yield and quality. Traditionally, crop pests and diseases are monitored by visual inspection of individual plants, which is time-consuming and inefficient. Besides, the distribution of different infected wheat patches are hard to identify through manual scouting. However, the spatial scale difference of remote sensing observation directly affects the remote sensing diagnosis mechanism and monitoring method of pests and diseases. The differences in pest and disease characterization and monitoring mechanisms promote the development of the remote sensing-based monitoring technology at different spatial scales, and the complementarity of multi-spatial data sources (remote sensing, meteorology, plant protection, etc.) increase the chance of the precision monitoring of the occurrence and development of pest and disease. As a non-destructive way of collecting ground information, remote sensing technologies have been proved to be feasible in crop pests and diseases monitoring and forecasting. Meanwhile, many crop diseases and pests monitoring and alarming systems have been developed to manage and control agricultural practices. Based on the description of physiological mechanism that crop diseases and pests stressed spectral response, some effective spectral wavelengths, remote sensing monitoring technologies, and crop pests and disease monitoring and forecasting system were summarized and sorted in this paper. In addition, challenge problems of key technology on monitoring crop diseases and pests with remote sensing was also pointed out, and some possible solutions and tendencies were also provided. This article detailed revealed the researches on the remote sensing based monitoring methods on detection and classification of crop pests and diseases with the challenges of regional-scale, multi-source, and multi-temporal data. In addition, we also reviewed the remote sensing monitoring of pests and diseases that meet the characteristics of different remote sensing spatial scale data and precise plant protection and control needs. Finally, we investigated the current development of the pest and disease monitoring systems which integrated the research and application of the existing crop pest and disease monitoring and early warning model. In summary, this review will prove a new perspective for sustainable agriculture from the current researches, thus, new technology for earth observation and habitat monitoring will not only directly benefit crop production through better pest and disease management but through the biophysical controls on pest and disease emergence. Application of UAVs, image processing to insect/disease detection and control should be directly transferable to other pests and diseases, with feedbacks into UAV and EO capabilities for the mapping and management of these agricultural risks. Similarly, these vision systems open other possibilities for farm robotics such as mechanical rather than manual pesticide usage for below crop canopy pest surveying.

Key words: crop; remote sensing; pests and diseases; monitoring; future prospects